LONDON'S GLOBAL UNIVERSITY

UCL

Integrated Approaches to Digital-enabled Design for Manufacture and Assembly: A Modularity Perspective and Case Study of Huoshenshan Hospital in Wuhan, China

Tan Tan

BArch, MSc

Supervised by:

Prof Grant Mills

Dr Eleni Papadonikolaki

A thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

The Bartlett School of Sustainable Construction

University College London (UCL)

2019 – 2023

Declaration of Ownership

I confirm that I have read and understood the guidance on plagiarism. I understand the meaning of plagiarism and that I may be penalized for submitting work that has been plagiarized. If I have been asked to submit a hard copy, I understand that the work cannot be assessed unless both the hard copy and the electronic versions are handed in. I declare that all material presented in the accompanying work is entirely my own words except where explicitly and individually indicated and that all sources used in its preparation and all quotations are clearly cited.

Total word count: 69534

Acknowledgement

After completing the first three months of my PhD, I returned to Wuhan to celebrate Chinese New Year. Little did I know that the next five days would alter the course of my PhD journey. Wuhan, for the first time in modern history, announced a city-wide lockdown in response to the outbreak of COVID-19, leaving me stranded with no clear timeline for when the lockdown would be lifted and no way to travel back to London for my studies. I reached out to my PhD supervisors, Prof Grant Mills and Dr Eleni Papadonikolaki, in a state of panic. In my email, entitled 'urgent inquiry', I explained the dire situation, informing them of the army takeover and the ban on citizens leaving the city, and expressing my concerns about having to put my studies on hold temporarily. To my great relief, my supervisors responded immediately, offering words of comfort, support, and invaluable advice. They assured me that I could continue my studies, even during the lockdown. It was during this time that Grant sent me a link from the BBC about a 1,000-bed emergency hospital that was to be built in Wuhan in just ten days. This unexpected emergency presented a unique research opportunity, and I decided to settle down and collect data about the project as a case study, marking the beginning of my PhD thesis. As I reflect on my academic journey, I feel a sense of satisfaction and gratitude. The journey itself has been its own reward, and I owe a debt of thanks to my two supervisors, Grant and Eleni, for their guidance and support. Their wisdom and insights have been illuminating and instrumental in helping me complete this journey. Additionally, I am grateful for the many mentors, colleagues, and friends who have accompanied me on this path, including Prof Wilson Lu, Dr Fan Xue, Dr Ke Chen, Dr Jinying Xu, among others. Their wisdom, camaraderie, and accomplishments have consistently inspired me to move forward. Lastly, I would like to express my gratitude to my parents and grandparents for giving me life and the opportunity to explore the world with curiosity. I am proud to share the joy of completing this PhD journey with them.

Abstract

Countries are trying to expand their healthcare capacity through advanced construction, modular innovation, digital technologies and integrated design approaches such as Design for Manufacture and Assembly (DfMA). Within the context of China, there is a need for stronger implementation of digital technologies and DfMA, as well as a knowledge gap regarding how digital-enabled DfMA is implemented. More critically, an integrated approach is needed in addition to DfMA guidelines and digital-enabled approaches.

For this research, a mixed method was used. Questionnaires defined the context of Huoshenshan Hospital, namely the healthcare construction in China. Then, Huoshenshan Hospital provided a case study of the first emergency hospital which addressed the uncertainty of COVID-19. This extreme project, a 1,000-bed hospital built in 10 days, implemented DfMA in healthcare construction and provides an opportunity to examine the use of modularity. A workshop with a design institution provided basic facts and insight into past practice and was followed by interviews with 18 designers, from various design disciplines, who were involved in the project. Finally, multiple archival materials were used as secondary data sources.

It was found that complexity hinders building systems integration, while reinforcement relationships between multiple dimensions of modularity (across organisation-process-product-supply chain dimensions) are the underlying mechanism that allows for the reduction of complexity and the integration of building systems. Promoting integrated approaches to DfMA relies on adjusting and coupling multi-dimensional modular reinforcement relationships (namely, relationships of modular alignment, modular complement, and modular incentive). Thus, the building systems integrator can use these three approaches to increase the success of digital-enabled DfMA.

Keywords: Modularity, DfMA, Digitalisation, Healthcare Construction, Case Study

Impact Statement

This research has theoretical implications for the integrated approaches to DfMA and practical implications for those who wish to implement digital-enabled DfMA for healthcare construction. This research addresses challenges and modularity strategies of digital-enabled DfMA, as well as integrated approaches to cope with those challenges. Parts of this research have been published in eight research papers—four journal papers, one book chapter and three conference papers. A journal paper derived from this thesis has been published in the *Journal of Management in Engineering* and was awarded Editor's Choice Selection. A journal paper has been published in the *Architectural Engineering and Design Management* and was awarded Most Downloaded Paper Prize.

In practice, this research provides the following evidence-based conclusions related to integrated design engineering which are useful for design organisations engaged in healthcare construction and, more broadly, complex building types. It shows that the industry needs to focus on 1) the innovation and integration of digital design processes and the integration of DfMA strategies, not just the implementation of digital tools and DfMA strategies; 2) reducing the difficulty of designing complex building systems by deconstructing, reconfiguring, and integrating building systems; 3) promoting design capabilities by optimising reinforcement relationships of multi-dimensional modularity to enhance building systems integration.

The case study results show that reducing complexity is key to design organisations reaching integration in engineering projects. By introducing Wuhan's experience, this research can enlighten relevant practitioners on how to use design strategies to achieve rapid healthcare construction. Also, the extreme case demonstrates the existence of richer strategic possibilities for normal major healthcare construction in its design of products, processes, organisations, and supply chains. This research was strongly supported by CITIC, the design institute of Huoshenshan Hospital, which has led to wider benefits and impacts.

Contents

List of Tables

List of Figures

Abbreviations

AEC	Architectural Engineering and Construction
BIM	Building Information Modelling
COVID-19	Coronavirus Disease 2019
DfMA	Design for Manufacture and Assembly
DfX	Design for Excellence
ICU	Intensive Care Units
IoTs	Internet of Things
NHS	National Health Service
OSC	Off-Site Construction
RIBA	Royal Institute of British Architects
WHO	World Health Organisation

Glossary

The relationships between the key concepts in this research are shown in Figure 1. Overall, there are two categories of concepts. Those rooted in ‘modularity’, and those based in digital-enabled DfMA. The overarching relationship of the highest level is to use modularity to integrate the strategies of digital-enabled DfMA and reduce the complexity. Within ‘modularity’, there are two major sub-group concepts: the connotations of modularity and the relationships within modularity. This research highlights the multi-dimensional nature of modularity, including product modularity, process modularity, supply chain modularity and organisational modularity.

The two major types of relationships between multiple dimensions of modularity are reinforcement relationships and non-reinforcement relationships. The former refers to three types of relationships identified in the research: alignment, complement, and incentive. The alignment relationship has been widely explored in various industries, and the two major theories concerning it are the mirroring hypothesis and Fine’s three-dimensional modularity. This research argues that the reinforcement relationships between multiple dimensions of modularity support the integrated approaches to combining various strategies of digital-enabled DfMA, thereby contributing to building systems integration.

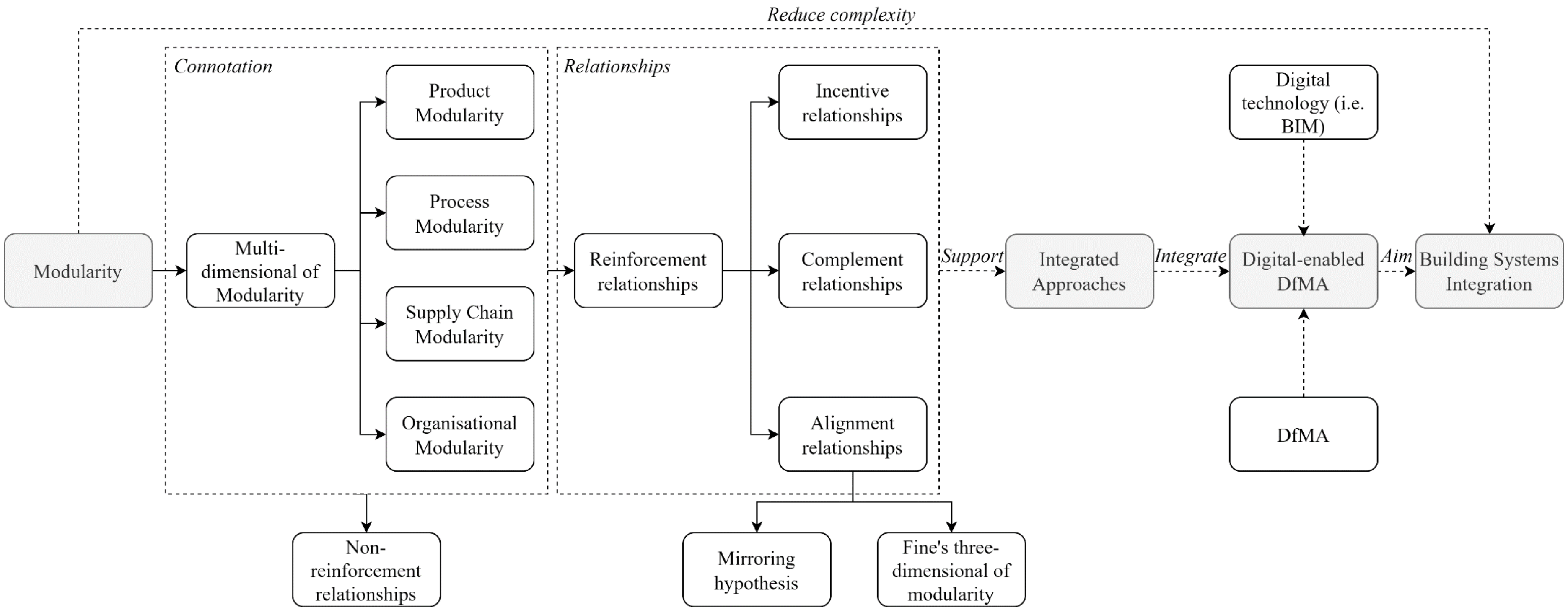


Figure 1 Relationships between concepts in the glossary

Abductive Reasoning is a form of reasoning that spans the complex and dynamic relationship between theoretical knowledge, empirical research, and professional best practice. It is often applied, using case studies, to understand a real-life context with multiple variables and multiple sources of evidence, in which phenomena boundaries are unclear. The process of abduction may start or finish with hypotheses or the selection of a premise or proposition. Abductive reasoning starts from a flexible position, simultaneously iterating from data collection and theory development.

Building Systems Integration is the ultimate goal of digital-enabled DfMA in healthcare construction. It is a process of physically and functionally bringing together all healthcare building systems—architectural, structural, ventilation and air conditioning, and electric—into a coordinated whole. It regards the healthcare building as a whole entity which is built on the reinforcement relationships of multi-dimensional modularity, grouping and integrating interdependent systems rather than considering a building as many independent building sub-systems designed simply through single or multiple DfMA guidelines.

Digital-enabled DfMA is a set of interacting and digital-enabled actions to manage the DfMA guidelines and processes for building systems integration by achieving reinforcement relationships among the multi-dimensional modularity strategy.

Fine's Three-Dimensional Modularity is a hypothesis about the relationships of multi-dimensional modularity. It claims that modular products tend to be designed and built by both modular processes and modular supply chains. Vice versa, integral products tend to be designed and built by both integral processes and integral supply chains.

Healthcare Construction deals with the interior and exterior building of healthcare facilities as well as ground-up projects. These healthcare facilities can be hospitals, medical nursing homes, medical laboratories, and so on. Hospitals are the key component of healthcare systems and range from large-scale cutting-edge hospitals to small speciality clinics. When constructing new healthcare facilities or working on existing facilities, there is a high level of attention paid to the health and safety of the hospital's staff and patients by the construction team working on the project.

Integrated Approaches to Design for Manufacture and Assembly relate to DfMA, a design methodology intended to enhance the realisation of design and construction physically and functionally through modularity strategies, reconfiguring the abstraction, emergence, and hiding of downstream knowledge in the design phase. The essence of DfMA is reducing system complexity and facilitating building systems integration. The main approach taken to DfMA is the integrated one, which balances and integrates all of DfMA's aspects rather than just implementing one or a few of them. Modularity strategies support such integrated approaches to DfMA. DfMA can be evaluated by various aspects, such as manufacturability and assemblability, as well as the level of integration between various hierarchical building systems. Integrated approaches to DfMA make trade-offs between various guidelines, strategies, and principles of DfMA to achieve the overarching benefits of building systems integration during the design process. Such approaches engender reinforcement relationships in the multi-dimensional modularity strategy to facilitate digital-enabled DfMA .

Modularity refers to a hierarchical system structure comprised of smaller sub-systems that can be designed independently and yet function holistically. Modularity emphasises the interdependence within and across modules and tries to use this to solve the complexities of component parts, hiding them behind abstractions and interfaces. The activity of dividing a product or system into interchangeable modules, namely the process of creating modularity, is called modularisation.

Modular Alignment Relationship is one of three possible reinforcement relationships between multiple dimensions of modularity. Modular alignment means that different dimensions of modularity reinforce each other and support the modularity by having similarly consistent level change within their own dimensions. Both Fine's Three-Dimensional Modularity and the Mirroring Hypothesis concern this relationship. Broadly, the relationship can adopt one of two patterns, namely 1) the same modularity principle can act on different dimensions of modularity at the same time (i.e. synchronised alignment), and 2) different modularity principles can act on different dimensions of modularity (i.e. asynchronous alignment).

Modular Complement Relationship is the second of three reinforcement relationships between multiple dimensions of modularity. It shows that the complexity of one dimension, that cannot deal with modularity principles, can be reduced by modularity principles in other dimensions of the multi-dimensional modularity. This relationship is also broadly divided into two cases. In one case, the integration challenges of a particular system are facilitated by sacrificing a certain level of modularity (i.e. subtraction complement). The second case involves a higher degree of modularity on the part of a dimension compared to the other dimensions, thus making that particular dimension more conducive to solving a particular problem (i.e. addition complement). Again, the benefits of the misalignment outweigh its negative effects.

Modular Incentive Relationship is the third of three reinforcement relationships between multiple dimensions of modularity. The incentivisation strategies of one dimensions of modularity indirectly motivate corresponding resources in another dimension, thereby creating a matching and reinforcing modularity strategy. The incentive relationship does not exist when the corresponding resources or matching strategies are not available.

Mirroring Hypothesis is a hypothesis about the relationships within the multi-dimensional modularity. It suggests that the organisational patterns of a development project, such as communication links, geographic collocation, and team and firm membership, correspond to the technical patterns of dependency in the system under development.

Multi-Dimensional Modularity (or multiple dimensions of modularity) refers to the characteristics of multiple sub-notions of modularity. It allows users to observe modularity from various viewpoints, including product modularity, process modularity, organisational modularity, and supply chain modularity.

Organisational Modularity is a type of multi-dimensional modularity used to reduce building systems' complexity in the DfMA organisational modularity. It describes a loosely coupled network of autonomously operating, self-contained units within an organisation. These units have a low level of interaction with each other but a high level of awareness of each other through standard collaboration rules, which can be flexibly recombined for different projects into a variety of organisational configurations.

Process Modularity is a type of multi-dimensional modularity used to reduce building systems' complexity in the DfMA process modularity. It is mainly used for planning purposes as it describes the degree to which a process can be deconstructed into modules for parallel execution. Thus, it corresponds to 'modularity-in-production'. Specifically, process modularity means standardising manufacturing sub-processes to be re-sequenced easily or facilitate open inter-change for new modules' 'plug-and-play'. The three principles of process modularity are (1) process standardisation, (2) process resequencing, and (3) process postponement.

Product Modularity is a type of multi-dimensional modularity used to reduce building systems' complexity in the DfMA product modularity. It corresponds to 'modularity-in-design' and is a product design strategy which uses standardised and interchangeable components for the configuration of various products.

Reinforcement Relationships mutually reinforce the integration of multiple dimensions of modularity. These relationships involve three sub-relationships, namely alignment relationships, supplementary relationships, and incentive relationships.

Supply Chain Modularity is a type of multi-dimensional modularity used to reduce building systems' complexity in the DfMA supply chain modularity. It emphasises the interdependence within and independence across certain supply functions or tasks. It also refers to whether certain supply functions or tasks are conducted by a single supplier or several and whether they can be explicitly distinguished from other functions or tasks, thus aiming to mitigate the complexities of supply chain coordination.

Chapter 1 Introduction

1.1 Research context

1.1.1 Healthcare facilities

Healthcare facilities consist primarily of hospitals, nursing homes, and medical laboratories. Hospitals, ranging from large, cutting-edge hospitals to small speciality clinics, are vital components of healthcare systems (Kobus et al., 2008). Many centuries ago, physicians would treat upper-class patients at home, and architects designed hospitals as religious institutions to administer care to patients who could not afford house calls. Patient wards expanded over time, but also became unsanitary and prone to spreading disease (Burpee, 2008; Guenther & Vittori, 2008; Verderber, 2010).

Modern hospitals are staffed by professionally trained doctors, nurses, and paramedical clinicians and are often funded by governments, health organisations, and health insurance companies. The World Health Organization (WHO) (2023) describes a hospital as a healthcare institution that provides patient treatment with specialised health science, auxiliary healthcare staff, and medical equipment. Hospitals are complex facilities that combine wards, office buildings, laboratories, and warehouses. The dynamics of care patterns within the healthcare industry and relationships with other facilities add to the complexity of designing healthcare facilities. The design of healthcare facilities (i.e. healthcare construction) and health services are closely linked. The development of healthcare facilities reflects the historical transformation of healthcare and can serve, to some extent, as a powerful tool to advance healthcare delivery (Burpee, 2008).

A major hospital is a vast 'therapy machine' that encompasses people and logistics. A typical healthcare facility depends on the state of its building(s) (e.g. structural and architectural elements and utilities), availability and sufficiency of staff, equipment, space and medical supplies, and easy accessibility (e.g. roads) for daily operations. Healthcare facilities have become increasingly complex as novel medical treatments have been developed; healthcare services have been transferred to communities, and diagnostic and interventional technologies have advanced (Kobus et al., 2008). Factors such as site planning, building monomers, medical equipment, construction materials, and indoor and outdoor environments impact healthcare design and construction.

1.1.2 Status-quo of healthcare construction

According to the World Health Statistics from WHO (2019), more than 50% of the world's 7.3 billion people cannot access the essential health services they need. It is especially difficult for people to access healthcare facilities in remote and underdeveloped areas. Therefore, a United Nations goal aims to improve health-related sustainable development and achieve universal health coverage by 2030. Designing advanced healthcare facilities will play a critical role in achieving this goal (Mills et al., 2015), but a lack of healthcare capacity and inefficient healthcare delivery are significant challenges (Iskandar et al., 2019; Wright et al., 2019).

Another serious challenge to sustainability is the energy consumption and greenhouse gas emissions of buildings, which account for approximately one-third of global emissions. Moreover, these emissions may double by 2050 (Wada et al., 2012). The United Nations estimates that urban populations will increase by 2.5 billion (Simkin et al., 2022). The outbreak of the Coronavirus Disease 2019 (COVID-19) pandemic in late 2019 has reinforced the global consensus on the existence of these challenges by exacerbating capacity shortages and inducing a crisis in healthcare facilities. Some countries are attempting to quickly expand their healthcare capacity and reduce the speed with which the virus spreads through rapid healthcare construction projects (Pan & Zhang, 2022).

The urgent need for healthcare services has accelerated the development of healthcare facilities around the world. In 2019, the total worldwide value of healthcare construction underway was $400 billion (Ellis, 2019). With a capital portfolio of £21 billion, healthcare is the second-largest area in the UK government's major projects portfolio, and major deliveries have been planned since 2020 (Mills et al., 2020). However, construction delays, cost overruns, and productivity have remained largely unchanged since before the pandemic. An advanced design approaches should improve these deficiencies.

Many industry reports have criticised the inefficiency or failure of healthcare construction (Iskandar et al., 2019; Wright et al., 2019). Even prior to the COVID-19 pandemic, politicians and the public regularly urged health service providers, such as the UK National Health Service (NHS), to provide more hospital beds, operating space, and treatment rooms with limited budgets (Clough, 2022). COVID-19 has exacerbated shortages and driven increased appeals for increased capacity (Weissman et al., 2020). Efforts to refurbish operating theatres and recovery areas into COVID-19 Intensive Care Units (ICU) have caused a severe shortage of healthcare facilities, and many NHS Trusts have long waiting lists for both major (life threatening) and minor surgical procedures (Clough, 2022). NHS Trusts might turn to advanced design approaches to rapidly construct new modular facilities. The preference for repeatability over modularity exists not just in the UK. Worldwide, healthcare construction often experiences mis-performance. Therefore, adopting an advanced design approach is critical for dealing with climate challenges and healthcare shortages (Mills et al., 2020).

1.2 Problem statement

1.2.1 Challenges of offsite technologies in healthcare construction

The traditional construction method is struggling to both keep pace with the rapidly increasing demand for healthcare services and adapt to emerging requirements (Pan & Zhang, 2022). Awareness and acceptance of Off-Site Construction (OSC) for healthcare construction have gradually increased in recent years. OSC is an advanced pathway to accelerate capability development and revolutionise traditional healthcare delivery (Adebayo et al., 2006; Pan &

Zhang, 2022). For healthcare facilities that use OSC, some or all components are manufactured in off-site factories rather than at hospital locations and then transported to the construction sites for assembly.

The healthcare sector has a long history of implementing OSC (Adebayo et al., 2006). According to archaeologists, the earliest use of OSC occurred in the British Isles during the Roman era (Gibb, 1999). The largest of the construction was the Legionary Fortress at Inchtuthil, Scotland, built between AD 83 and 86. Inchtuthil's 170 buildings include a large 600-bed hospital (Adebayo et al., 2006). The modern off-site built hospital originated in 1854, soon after Britain entered the Crimean War. Due to the decrepit conditions in the Turkish Selimiye Barracks at Scutari that the British had converted into an army hospital, the British government erected the first modern offsite-built hospital (see Figure 2) that had been transported by ship to the installation site in Crimea in 1855 (Verderber, 2015).

Since the outbreak of COVID-19, various countries have taken advantage of OSC to rapidly construct and retrofit emergency healthcare facilities (Pan & Zhang, 2022). OSC also offers a promising means for dealing with excess temporary or non-temporary COVID-19 medical wards by disassembling and recycling their materials in a sustainable way. Some governments have published policies to expand their healthcare capacity through off-site and modular construction techniques (Pan & Zhang, 2022).

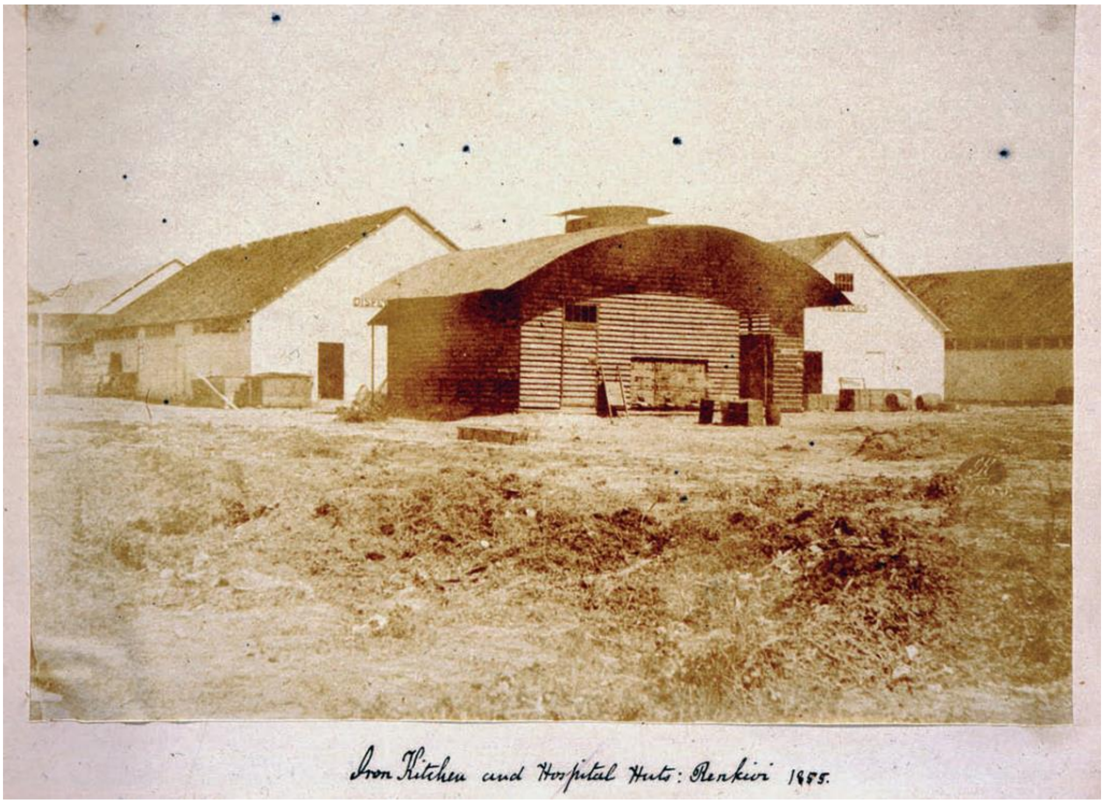


Figure 2 Brunel’s revolutionary off-site hospital built in 1855

However, some people question the suitability of OSC for healthcare construction (Pan & Zhang, 2022), particularly of facilities beyond standardised wards and outpatient clinics. For example, flexibility is essential in healthcare construction, but OSC is ill-suited for incorporating last-minute design changes (Jang & Lee, 2018). In addition, many parts of healthcare construction are conventionally procured on a project-by-project basis, and they are designed, manufactured, and constructed as bespoke projects. Project-specific manufacturing results in high costs and slow production processes (Mittal et al., 2020; Tillmann et al., 2010).

Linear, fragmented, and non-repetitive production methods hinder the healthcare sector’s adoption of OSC; producing prefabricated buildings requires collaboration and interdisciplinary work across a variety of technical areas and with a variety of stakeholders (Abdul Nabi & El-adaway, 2020; Innella et al., 2019). A wide range of established professions and disciplines, which are represented by a variety of professional bodies and trade organisations, exist in the architectural, engineering, and construction industry (Emmitt, 2010). Inter- and transdisciplinary knowledge transfer creates severe challenges for productive interactions between the design, manufacturing, and assembly phases of a project. Complex-building settings and hyper environments (i.e. healthcare facilities) exacerbate those challenges (Adebayo et al., 2006).

To achieve high-quality patient care, future healthcare facilities should be built with the best available knowledge on medical science and modern health technology (Aalto et al., 2019). However, user-centric integrated design and innovation are serious challenges (Lahtinen et al., 2020). Therefore, a highly coordinated approach to learning and sharing information is paramount if healthcare construction professionals are to enable repeatability and standardisation between projects and align commercial interests and building incentives around a single programme that challenges conventions and delivers innovation.

1.2.2 Challenges of design for manufacture and assembly

A strategic approach to increasing productivity and sustainability in the healthcare construction sector is critical. Leading organisations and institutions are collaborating around the Design for Manufacture and Assembly (DfMA) philosophy. DfMA is a methodology where products are designed to facilitate downstream manufacturing and assembly to the extent possible (Gao et al., 2020; Tan et al., 2020). The Royal Institute of British Architects (RIBA) (2021), Singapore’s Building and Construction Authority (2016), the UK Infrastructure and Project Authority (2018), and the Hong Kong government (2018) are establishing principles, processes, and standards to achieve DfMA. The introduction of DfMA has challenged healthcare construction professionals to accelerate modern hospital manufacturing (see Figure 3).

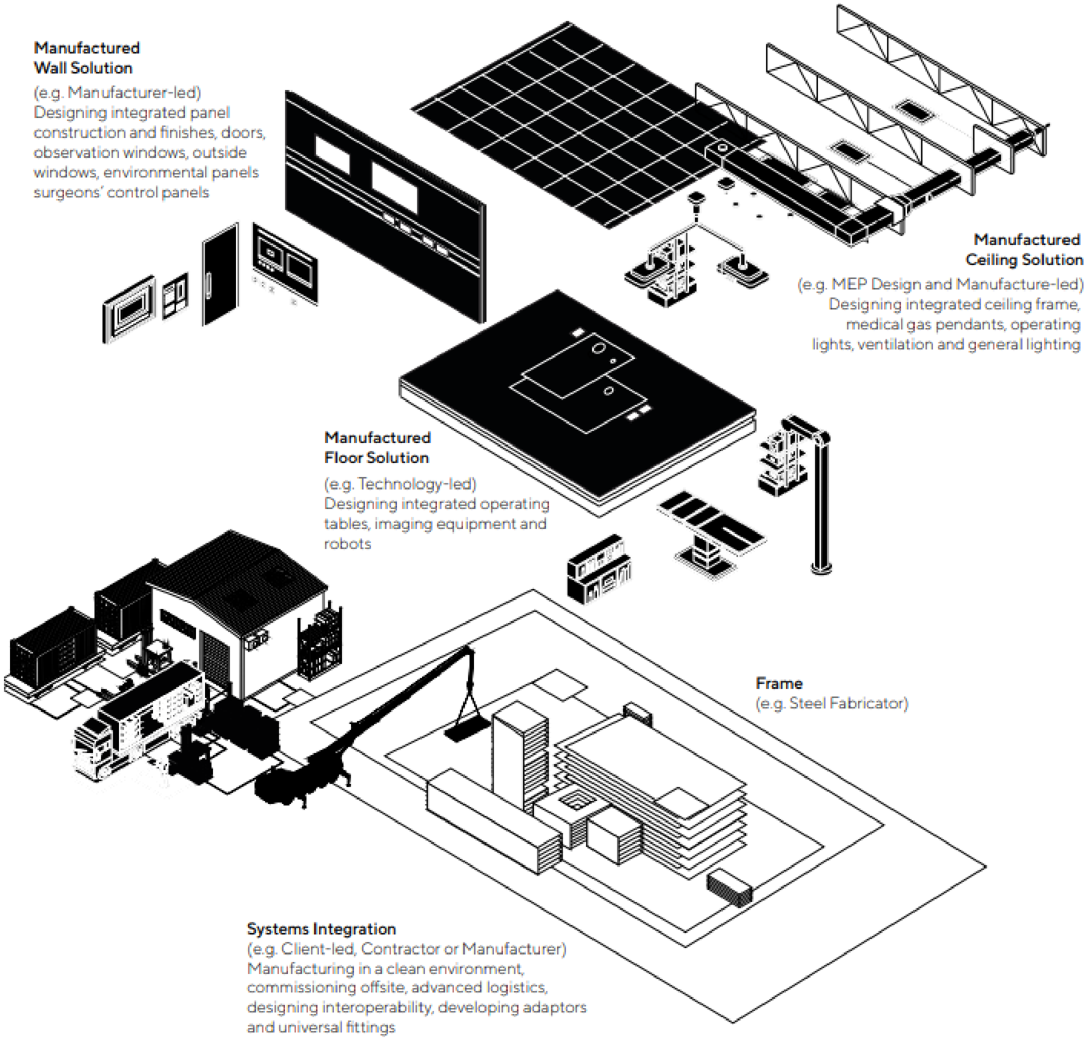


Figure 3 Flat-pack operation theatres using DfMA (Mills et al., 2020)

Nevertheless, transplanting DfMA from manufacturing to construction requires understanding the similarities and distinctions between the two industries. Manufacturing can be defined as the process of transforming materials and information into goods for the satisfaction of human needs (Chryssolouris, 2013). It is often linked to 'mass production', which uses machinery and information technologies to achieve cost-effective production (Crowley, 1998; Lanigan, 1992). Construction can be considered a production process with location-based products that involve significant onsite assembly, such as buildings, bridges, and roadways (Jewell et al., 2014).

Manufacturing and construction share many managerial practices. For example, both involve multiple stakeholders in the design, procurement, production, logistics, and supply-chain management (Winch, 2003). Compared to manufacturing, with its relatively standardised workflow, construction is a highly localised activity that involves using locally available resources and considering local geographic, economic, social, and climatic constraints to finish a project (Akanni et al., 2015). The site-specific, one-of-a-kind nature of construction projects makes it difficult to fully standardise routines (Aapaoja & Haapasalo, 2014; Jewell et al., 2014; Koskela, 1992).

Even though OSC resembles manufacturing and hence enables applying DfMA principles, they are not the same. In an OSC project, some major components, such as off-site precast yards, can be manufactured, but a considerable portion of the construction and assembly work must be conducted onsite. Fully modular integrated construction is not always the best choice (Lu et al., 2018). An OSC project's final product is still location based; it is constrained by site conditions and bespoke requirements from myriad clients. The dissimilarities between OSC and manufacturing necessitate scrutinising 'general' manufacturing DfMA guidelines to propose construction-oriented strategies suitable for healthcare construction.

1.2.3 Challenges of pioneering BIM for healthcare construction

Among all construction project types, healthcare construction has the highest risk of encountering major and unforeseen problems. Healthcare construction projects involve hundreds of stakeholders and suppliers. Adopting digital-enabled approaches, such as Building Information Modelling (BIM), is an increasingly prevalent topic in the contemporary literature on healthcare construction. BIM can transform traditional information management and integrate data from different disciplines (Eastman et al., 2011; Sacks & Pikas, 2021). BIM enables integrating various stakeholders horizontally while integrating information at different project stages vertically (Chang & Shih, 2013; Gaur & Tawalare, 2022). BIM, as a collaborative methodology, contributes to sharing project information throughout a building's life cycle (Emmitt & Ruikar, 2013; Meng et al., 2020). This research defines BIM as 'a set of interacting policies, processes and technologies generating a methodology to manage the essential building design and project data in digital formats throughout the building's life cycle' (Succar, 2009).

Many studies have shown BIM's profound impact on how healthcare projects are designed and implemented. Studies have reported the successful implementation of BIM in healthcare construction in different countries, including the Netherlands (Sebastian, 2011), Norway (Merschbrock & Munkvold, 2015), Australia (Mignone et al., 2016), the UK (Davies & Harty, 2013), and the US (Kokkonen & Alin, 2016). Many articles describe BIM as being incredibly beneficial in designing hospital spaces with numerous technical appliances and demanding performance requirements. However, implementing BIM is challenging in practices. Further evidence is needed to establish digital-enabled approaches' capacity to meet complicated design requirements in such areas as hygiene, safety, and equipment.

1.3 Knowledge gap

Future healthcare facilities should embrace advanced construction methods and integrated design approaches to deliver high-quality patient care. The emergence of COVID-19 has facilitated the diffusion of OSC in healthcare design (Pan & Zhang, 2022), which has been the subject of numerous studies. Pan et al. (2004) investigate the differences between conventional and DfMA processes by exploring the requirements for changing roles and the composition of design teams. However, many challenges exist related to OSC design, including the inability to freeze the design early and the complex interfaces between building systems (Pan et al., 2007). Pan et al. (2019) further highlight the importance of BIM in enabling advanced OSC design, such as BIM-based DfMA, which is, however, still in its infancy in the Architectural Engineering and Construction (AEC) industry. The need for introducing these evidence-based, construction-oriented, and digital-enabled DfMA guidelines for complicated healthcare design requirements, such as integrating different systems, necessitates further review and development. Specifically, an integrated design approach for OSC in healthcare construction should be established to better use of DfMA guidelines.

Modularity strategies could provide a strong basis to facilitate integrated design. Multi-dimensional modularity (or multiple dimensions of modularity) refers to the characteristics of multiple sub-notions of modularity. It allows users to observe modularity from various viewpoints, including product modularity, process modularity, organisational modularity, and supply chain modularity. Nevertheless, little is known about utilising the relationships between multiple dimensions of modularity in digital-enabled DfMA for healthcare. For example, Pan et al. (2004) and Pan et al. (2012) argue that it is necessary to integrate OSC requirements into the design process to realise OSC's benefits. Da Rocha et al. (2015) and Da Rocha and El Ghoz (2019) focus on product modularity in facilitating and integrating designs. Chen and Whyte (2021) develop a process modularity-based approach (i.e. combing digital twin and design structure matrix to understand design changes).

However, design activities that follow single-dimensional modularity strategy may not achieve building systems integration. Da Rocha and Koskela (2020) analyse the underdevelopment of product modularity in construction. Furthermore, Pan et al. (2008) suggest a misalignment exists between conventional procurement methods and levels of awareness about incorporating OSC (i.e. product modularity) into early designs. A growing body of research emphasises the utilisation of the multi-dimensional modularity for better integrated design. A significant knowledge gap is to understand how to utilising the relationships between multiple dimensions of modularity in healthcare digital-enabled DfMA.

There is a need for a transition to using the multi-dimensional modularity strategy to facilitate the design. This research seeks to achieve the integrated design from more than single-dimensional modularity strategy, representing a transition from a single-dimensional to a multi-dimensional modularity strategy. Previous studies have explored various strategies to facilitate product modularity. Da Rocha and Kemmer (2018) investigate the alignment relationship between product modularity and process modularity, the positive impacts of alignment on building design, and the negative impacts of misalignment between product modularity and process modularity. However, the potential positive impacts of the misalignment relationship between multiple dimensions of modularity have attracted little attention. Hall et al. (2020) investigate the alignment relationship between product modularity and organisational modularity (i.e. mirroring hypothesis) at the construction-firm level; however, this alignment relationship between product modularity and organisational modularity (i.e. mirroring hypothesis) at the project level has not been explored or validated for building designs. Tee et al. (2019) identify a complement relationship between product modularity (i.e. ‘modularity in design’ or ‘modular design’) and organisational modularity at the project level. Loosely coupled modular products can be designed through a highly integrated organisational collaboration, demonstrating that aligning multi-dimensional modularity is not always the best design practice and that misalignment relationships also exist. Nevertheless, complement relationships have not been explored within other dimensions of modularity, such as process and supply chain levels. There is a gap to fully understand the relationships between the multi dimensions of modularity, including alignment relationships and complement relationships, and how these relationships facilitate integrated design.

In summary, both Hall et al.’s (2020) alignment relationship and Tee et al.’s (2019) complement relationship are reinforcement relationships between multiple dimensions of modularity to facilitate continuous collaboration and integration. However, research into these multi-dimensional modularity relationships in the AEC industry, especially for building design at the project level, is still limited. The importance of using a multi-dimensional perspective to facilitate modularity is also emphasised by Pan et al. (2019), who propose five visions for the multi-level framework, but further empirical evidence is needed to support and build on these recommendations. Therefore, this research addresses the research gap related to the lack of a comprehensive reinforcement strategy between multiple dimensions of modularity to achieve integrated approaches to DfMA; the outcomes of this research can facilitate and integrate advanced designs (i.e. digital-enabled DfMA) for building systems integration.

1.4 Research aim and objectives

This PhD thesis investigates *the implementation of digital-enabled DfMA in the first COVID-19 emergency hospital in Wuhan, China.* This research is to combine existing studies of modularity and digital-enabled DfMA to understand the relationships between DfMA and systems integration. It is therefore necessary to understand the reinforcement relationships between multiple dimensions of modularity, including different types of reinforcement relationships and how they work in empirical settings. This research aims to propose integrated approaches based on the achievement of reinforcement relationships to facilitate digital-enabled DfMA for building systems integration in healthcare construction.

Huoshenshan Hospital, the first emergency modular hospital in Wuhan to combat COVID-19, is the case study used to perform three research objectives. This research investigates the context of the case and also the case itself to better understand the uniqueness and revealing of Huoshenshan Hospital. Three objectives includes:

Objective 1: reveal the context of the single case, namely perceived practices and strategies from practitioners for the use of digital-enabled approaches (i.e. BIM) and DfMA in China's healthcare construction industry;

Objective 2: explore the implementation of digital-enabled approaches (i.e. BIM) and DfMA in Huoshenshan Hospital, and revealing their underlying modularity principles in product, process, organisation and supply chain; and

Objective 3: explore integrated approaches to facilitate the implementation of digital-enabled DfMA in Huoshenshan Hospital, and unpacking different types of reinforcement relationships and how they work in digital-enabled DfMA.

1.5 Research questions

The primary research question of this thesis addresses the research context presented above: '*How can digital-enabled DfMA be implemented effectively in healthcare construction through integrated approaches to achieve building systems integration?*' This question is proposed to guide the development of an integrated approaches for healthcare construction projects with the understanding and utilisation of reinforcement relationships between multiple dimensions of modularity. However, answering this question requires knowledge of designer perspectives and empirical evidence related to digital-enabled DfMA and modularity theory in healthcare construction. Unfortunately, the existing literature outlined above does not provide a sufficient knowledge base for answering the primary question. Therefore, this research poses three secondary research questions within the context of China's healthcare construction:

1) What are the perceived practices and strategies from practitioners for the use of digital-enabled approaches (i.e. BIM) and DfMA in China's healthcare construction industry?

2) How are digital-enabled approaches (i.e. BIM) and DfMA implemented in Huoshenshan Hospital through their underlying modularity principles?

3) How to facilitate the implementation of digital-enabled DfMA in Huoshenshan Hospital through integrated approaches?

1.6 Research design and methodology

1.6.1 Research methodology

This research employs an ontological position on critical realism and an epistemological position on interpretivism; it uses an abductive reasoning methodological approach for a single case analysis. Figure 4 details the research methods. Firstly, this research uses a survey to understand the practices of digital technologies and DfMA practices in Chinese healthcare construction. This initial investigation involves an online questionnaire survey and 13 semi-structured interviews to understand the industry context. The survey involves quantitative research that follows a descriptive design and qualitative research that uses interview-based studies. Secondly, the main phase of the research is a single case analysis method involving three steps: a focus group, 18 interviews of designers, and an archival study, which formed the basis and validation of the case.

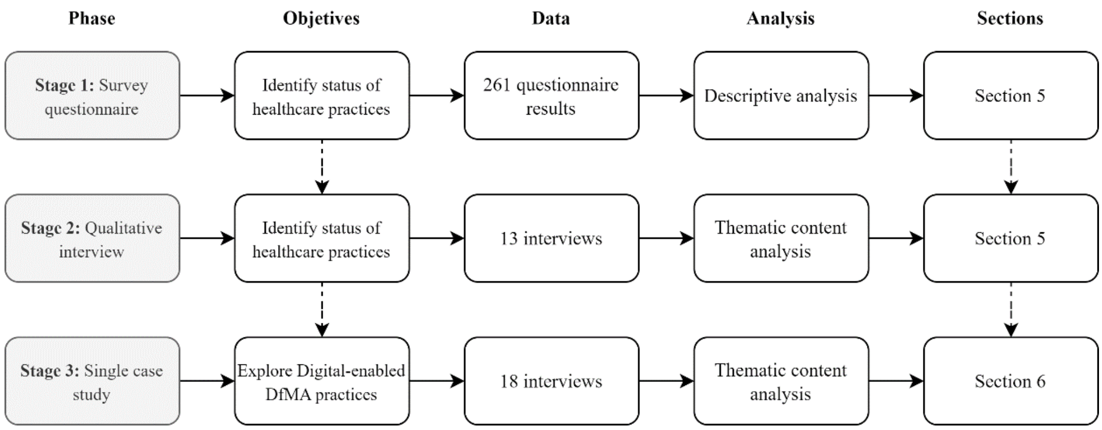


Figure 4 Research methods

1.6.2 Thesis structure

As shown in Figure 5, the presentation of the thesis structure follows a narrowing down approach from the macro level (i.e. industry surveys) to the middle level (i.e. semi-structured interviews with industry practitioners) and finally to the micro level (i.e. a single case study for a hospital project). Correspondingly, there are three phases. The first phase investigates current digital-enabled approaches (i.e. BIM) and DfMA practices in healthcare construction. The second phase investigates how DfMA is interpreted and implemented in healthcare construction. The third phase explores integrated approaches for DfMA for healthcare construction.

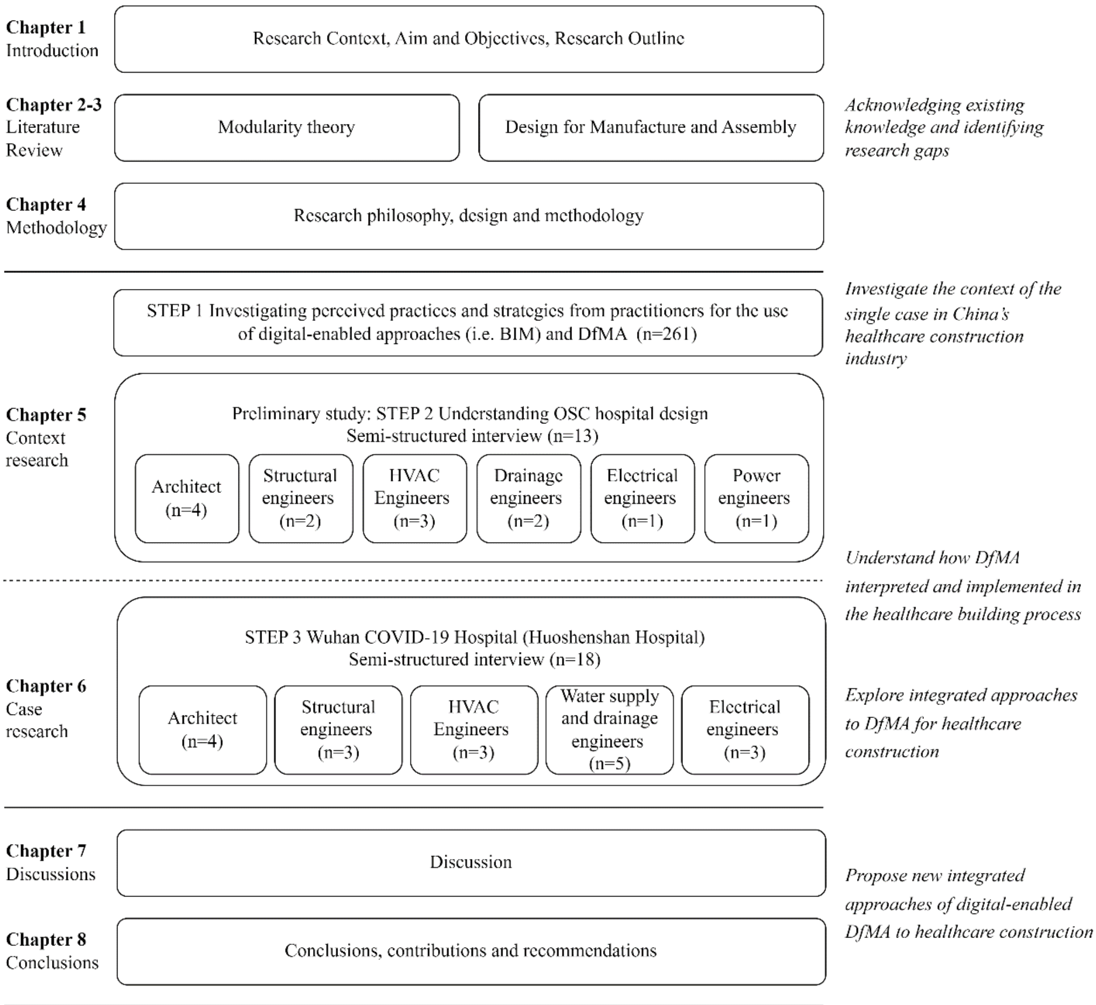


Figure 5 Research map

This thesis contains eight chapters. The remaining seven chapters consist of four main parts: (1) literature and theoretical background; (2) research methodology; (3) case study; (4) discussion and conclusions.

Chapter 2 comprehensively illustrates modularity theory, which is used as a foundation for the case interpretation, and modular integrated approach development. This chapter starts from the definition of modularity in wider contexts to the multiple dimensions of modularity and the relationships between them. Finally, it discusses the literature about value of modularity in design and construction.

Chapter 3 describes the development of DfMA in the manufacturing and AEC industry. This chapter introduces digital-enabled DfMA, and further explore its state-of-art combination with BIM, especially in healthcare construction settings. It finally discusses prospects and challenges of DfMA.

Chapter 4 presents this thesis's methodology from research philosophy, approach, methodology rationale, case selection, data collection to data analysis. This chapter establishes the rationale of a critical realism ontological and interpretivism epistemological single case study within its specific empirical settings of China's healthcare construction and COVID-19 challenges.

Chapter 5 presents the results of case context. This chapter summarises the results of current practices for digital-enabled approaches (i.e. BIM) and DfMA in the general China's healthcare construction. It aims to provide the context and comparison for the uniqueness and revealing of the single case – Huoshenshan Hospital.

Chapter 6 presents the results of Huoshenshan Hospital itself. The results includes case descriptions, building system categorisations, DfMA strategies, digital strategies, and modularity principles adopted in design.

Chapter 7 discusses the research results and integrated approaches; This chapter firstly discusses the combination of DfMA and systems integration and its challenges. It then goes to the integrated approaches to digital-enabled DfMA, and response to existing knowledge and gap of alignment and reinforcement relationships between multiple dimensions of modularity. It finally discusses three major modular reinforcement relationships identified in this research about their mechanisms and capabilities for DfMA and building systems integrations.

Finally, chapter 8 presents conclusions of the research, including summary of insights, research achievements and knowledge contributions, implications, limitations and future directions.

1.7 Expected knowledge contributions

This research involved the use of a literature review and surveys to address the knowledge contribution to the industry context of the case study and knowledge exploration. A literature review was first conducted, including an analysis of DfMA and BIM. An extensive questionnaire was then employed resulting in 183 valid responses to gauge the responses of China's healthcare construction participants. Follow-up interviews were subsequently conducted to verify some of the possible insights. For the knowledge contribution to modularity strategies of digital-enabled DfMA, a case study of Huoshenshan Hospital was used to explore the objectives of the research based on abductive reasoning. Data collection methods included a workshop, 18 interviews (covering design leaders and participants from all design disciplines, representing approximately one-third of the total project designers), and subsequent archival analysis.

As shown in Figure 6, this research provides evidence-based knowledge to the gap of modularity integrated approaches to DfMA through the exploration of reinforcement relationships. Three types of reinforcement relationships were identified, including modular alignment, complement and incentive relationships, which furthers current understanding and knowledge of relationships between multiple dimensions of modularity, and also how these relationships influence the process and result of design. The knowledge contribution builds on existing literature about digital-enabled DfMA and building systems integration to facilitate the area development of DfMA and systems integration.

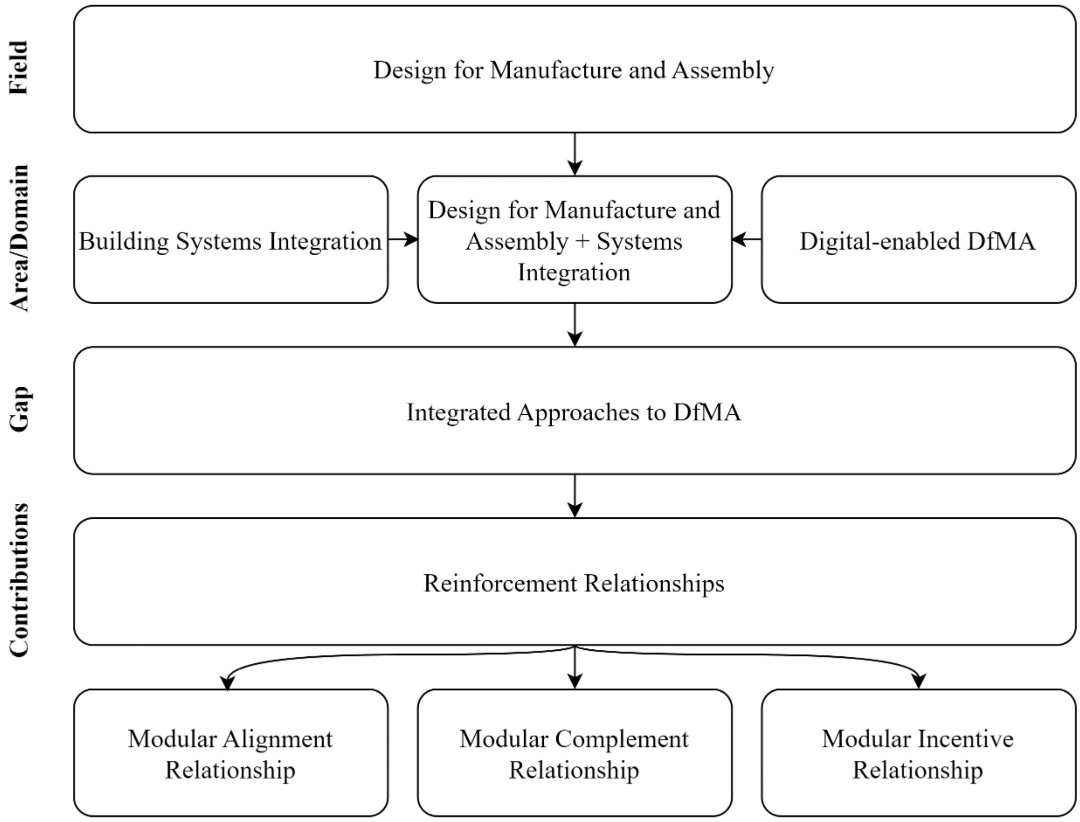


Figure 6 Research contributions

The research first builds on the knowledge of alignment relationships (i.e. mirroring hypothesis) and extends beyond Hall et al.'s (2020) construction-firm-level validation to identify the alignment relationship between product modularity and organisational modularity (i.e. mirroring hypothesis) at the project level to add knowledge to DfMA and systems integration. Modular alignment relationship is the one of three possible reinforcement relationships between multiple dimensions of modularity. Modular alignment means that different dimensions of modularity reinforce each other and support the modularity by having similarly consistent level change within their own dimensions. Both Fine's Three-Dimensional Modularity and the Mirroring Hypothesis concern this relationship. Broadly, the relationship can adopt one of two patterns, namely 1) the same modularity principle can act on different dimensions of modularity at the same time (i.e. synchronised alignment), and 2) different modularity principles can act on different dimensions of modularity (i.e. asynchronous alignment).

Second, the research extended Tee et al.'s (2019) complement relationships for integrated design in projects through other dimensions of modularity to integrate modular approaches. Modular complement relationship is second of three reinforcement relationships between multiple dimensions of modularity. It shows that the complexity of one dimension, that cannot deal with modularity principles, can be reduced by modularity principles in other dimensions of the multi-dimensional modularity. This relationship is also broadly divided into two cases. In one case, the integration challenges of a particular system are facilitated by sacrificing a certain level of modularity (i.e. subtraction complement). The second case involves a higher degree of modularity on the part of a dimension compared to the other dimensions, thus making that particular dimension more conducive to solving a particular problem (i.e. addition complement). Again, the benefits of the misalignment outweigh its negative effects.

Third, the research identified novel modular incentive relationships. Modular incentive relationship is the third of three reinforcement relationships between multiple dimensions of modularity. The incentivisation strategies of one dimensions of modularity indirectly motivate corresponding resources in another dimension, thereby creating a matching and reinforcing modularity strategy. The incentive relationship does not exist when the corresponding resources or matching strategies are not available.

This research found that all three reinforcement relationships that exist in organisation-process-product-supply-chain dimensions can be used to facilitate integrated approaches for digital-enabled DfMA, and that there are two key characteristics of these reinforcement relationships. First, they can reduce the complexity of digital-enabled DfMA, namely the organisation-process-product-supply-chain dimensions. Second, they can be used to integrate various digital-enabled DfMA strategies, eliminating the fragmented use of digital tools and DfMA guidelines. Based on these findings, it is argued that architects can take the lead in integrating all four dimensions during the design process and utilise the three reinforcement relationships for integrated approaches to DfMA. As a result, integrated approaches achieve digital-enabled DfMA in the multi-dimensional coupled state of four dimensions, thereby facilitating building systems integration.

1.8 Chapter summary

This chapter briefly describes the background of the research, the current state of healthcare construction and challenges, the research objectives and questions, the methodology, and the research contributions. In the next chapter, the primary theoretical foundation of this research—modularity theory—is reviewed to illustrate how digital-enabled DfMA can address the challenges in healthcare construction.

Chapter 2 Modularity in Design and Construction

2.1 Introduction

This chapter focuses on the main theoretical perspective of this research. It begins with a definition of modularity and discusses multi-dimensional modularity. This chapter then outlines the relationship between these four dimensions of modularity in the existing literature; it also discusses the value of modularity in design, i.e. how modularity principles address the complexity of design itself. The final section provides an overview of the development of modularity across the AEC industry, thereby the challenges and strategies of integrating complex building systems.

2.2 Definition of modularity

The generation of modularity theory can be traced back to previous theoretical concepts from many years ago. For example, Simon (1962) proposes the concept of ‘near decomposability’, implicating systems can be reconstructed into component sub-systems for complexity reduction. After that, Starr (1965) pioneers the concept development of ‘modular production’ to describe the capacity of design for manufacture in parts that can be assembled in multiple approaches. Furthermore, Weick (1976) puts forward a similar conceptual terminology named ‘loose coupling’, referring to systems having responsive elements, preserving physical or logical separateness, and characterising their advantage in localised adaptation.

These close theoretical concepts provided the basis for the development and evolution of modularity but also led to a long-standing difficulty in reaching a consensus of rigorous definitions (Salvador, 2007). Terminologies like ‘module’, ‘modular’, ‘modularity’, and ‘modularisation’ are used interchangeably in hundreds of academic papers on different subjects. Nuances of modularity exist and vary somewhat based on contextual background, such examples ranging from several fields of science (i.e. biology, ecology, cognitive science), technology (i.e. modular programming, software design, self-reconfiguring modular robotic), industry (i.e. construction, industrial design, manufacturing, organisational design), and culture (i.e. new media, modular art).

Modularity refers to a hierarchical system structure consisting of smaller sub-systems that can be designed independently but operates as a holistic system (Baldwin et al., 2000; Ulrich, 1995). Modularity is a relative system attribute (Baldwin et al., 2000). Every system is somewhat modular (Campagnolo & Camuffo, 2010). Various industries have their specific definition, respectively. In engineering design, modularity refers to products, processes, and resources that fulfil various functions by combining distinct building blocks (Kusiak, 2002). In technology and organisation, modularity refers to breaking up a complex system into discrete pieces upon a standardised architecture for their interactive communication only through standardised interfaces (Langlois, 2002). In the AEC industry, modularity refers to building construction from many instances of standardised components (Ulrich, 1994). In recent years, some studies have systematically reviewed the definition of modularity (Campagnolo & Camuffo, 2010; Pandremenos et al., 2009; Salvador, 2007; Sonego et al., 2018). A consensus is that they emphasise interdependence within and independence across modules and try to use this feature to solve complexity by hiding the complexity of parts behind abstractions and interfaces (Baldwin et al., 2000). Baldwin and Clark (2006) indicate three purposes of modularity: (1) to make complexity manageable; (2) to enable parallel work; and (3) to accommodate future uncertainty. Baldwin et al. (2000) capture the essence of modularity from three ideas: (1) abstraction, (2) information hiding, and (3) interface (see Figure 7).

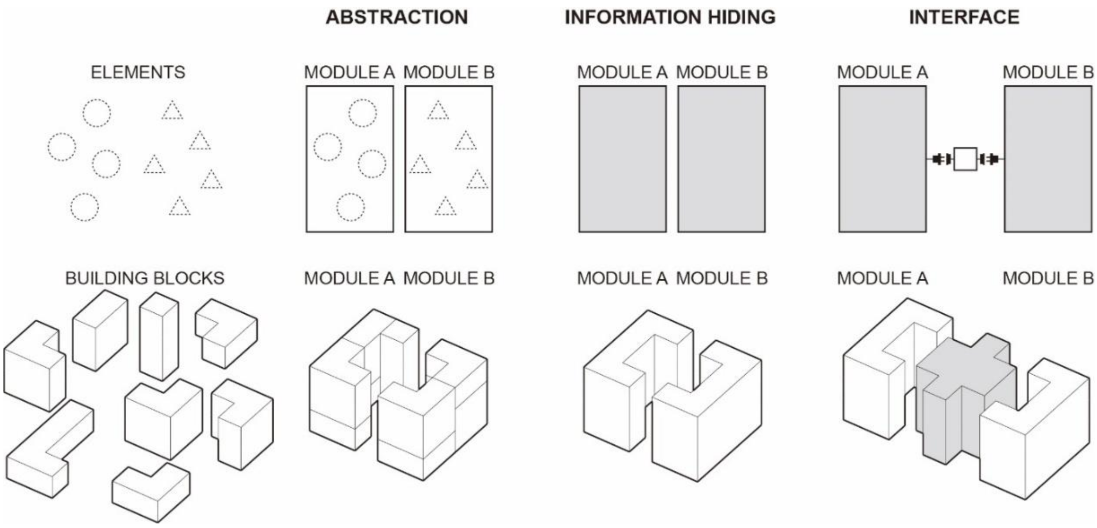


Figure 7 Abstraction, information hiding and interface

For the first term, in Oxford English Dictionary, *abstraction* is 'the act of separating in thought'. In modularity, *abstraction* further means to hide the elements' complexity (Baldwin et al., 2000). It is usually used as a complexity mastering strategy by outstanding essential features of an object without including background or inessential detail (Graham, 1994), thus providing crisply defined conceptual boundaries (Booch, 1990). *Abstraction* can be regarded as both a process and an entity. As a process, it represents extracting the essential details and ignoring the inessential details about objects. As an entity, it stands for a model, a view, or other focused representation of an actual item. In practice, many types of *abstraction* exist, such as functional abstraction, process abstraction, data abstraction, and object abstraction (Berard & Twain, 1993).

For the second term, Parnas (1972) introduces *information hiding* to devise modular structures in software design. This term is perfectly general for any complex system (Baldwin et al., 2000) and refers to the fact that all information about a module (including data and functionality) is encapsulated and hidden from other modules unless specifically declared public (Graham, 1994). A module is characterized by its hiding information from other modules (Ghezzi et al., 1991). The principle of *information hiding* is central; meaning modules are used via their specifications rather than implementations. In practice, *information hiding* reduces redundant communication in modularity (Campagnolo & Camuffo, 2010).

For the third term, the *interface* is a shared linkage between components (e.g. people, information) for open inter-change and rules that control the flow of information (Voss & Hsuan, 2009). In essence, the *interface* as part of the public information set is a pre-established way to resolve potential conflicts between the interactive parts of the design. For products, Ulrich (1995) regards the *interface* between components as a solution for allocating product functions to physical components. For services, De Blok et al. (2014) further develop the definition of interface used in products by recognising two dimensions, namely interface entities (i.e. components or service providers) and interface aims (i.e. variety or coherence). The *interface* is known as 'visible' design rules across stakeholders. The *interface* over time and its standardisation represents a common and agreed-upon mechanism for interaction among a system's complementary product or process components (Baldwin et al., 2000).

Ulrich (1995) categorises various interface types of modularity, such as sectional, bus and slot modularity. Salvador et al. (2002) further classified slot-type modularity into combinatorial modularity and component swapping modularity. These four types of modularity distinguish from each other according to the diversity of interfaces and the use of main bodies (see Figure 8). In sectional modularity, modules interface with each other through identical interfaces, whereas in bus modularity, modules interface with a main body using identical interfaces in what is known as a bus interface. In both combinatorial modularity and component-swapping modularity, there is no identical interface that all modules share globally. However, some modules share a common interface locally, which is called a slot. Each module in combinatorial modularity has its own slots and can be connected to other modules that have the same type of slot. Alternatively, in component swapping modularity, modules interface with a main body through slots (Choi & Erikstad, 2017).

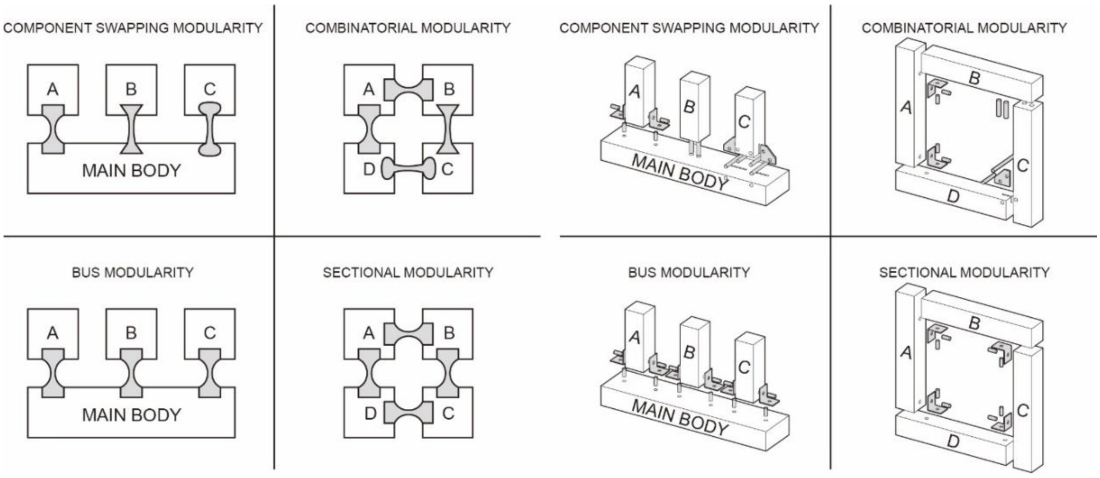


Figure 8 Typology of modularity

2.3 Multi-dimensional modularity

2.3.1 Product modularity

Product modularity as a sub-concept of modularity corresponds to 'modularity-in-design'. Product modularity is a product design strategy using standardised and interchangeable components to configure various products (Schilling, 2000). As a multi-faceted concept, there is little consensus on the definition of product modularity (Gershenson et al., 2003). Campagnolo and Camuffo (2010) classify definitions into three main categories. Firstly, from a functional perspective, product modularity considers the degree of modularity of product architectures which investigate the relationship between modules, functions, and interfaces. A product architecture can be defined by (1) the arrangement of functional elements, (2) the mapping from functional elements to physical components, and (3) the specification of the interfaces between interacting physical components (Ulrich, 1995). The differences between 'modular' product architecture and 'integrated' product architecture can be identified through these three aspects. Secondly, from a technical-oriented perspective, the rationale indicates the existence of an 'optimal' degree of product modularity.

In addition, various objectives of modularity lead to a more complex definition of product modularity (Gershenson et al., 1999; Ishii, 1998). For example, the objectives could be time-to-market, manufacture, assembly, logistics and disassembly. Thus, they have different modularity methods and measures. With the objective of manufacturability, the measure is to reduce the recycling time of the manufacturing process. With the objective of assembly, reducing assembling operations is the main measure. There is a strong relationship between the objectives, definition of modules, modularity method and measures. It is difficult to establish a one-for-all definition fitting each life-cycle phase. Therefore, a clear goal is essential for defining product modularity and ways of modularity (Campagnolo & Camuffo, 2010). Other research tries to adopt a mixed perspective for developing a modularity methodology by combining functional and life-cycle perspectives.

2.3.2 Process modularity

A process is defined as ‘a structured, measured set of activities designed to produce a specified output for a particular customer or market’ (Davenport, 1993). There are two views of the process in design. The technical perspective regards the architecture of the design process as a network of information dependencies between design tasks, which enhances the ability to consider logical precedencies and define the sequence of activities (Clarkson & Hamilton, 2000). The socio-technical perspective regards the architecture of the design process as a network of interdependent activities executed by people over time (Parraguez et al., 2019).

Process modularity, corresponding to ‘modularity-in-production’, mainly used for planning purposes, describes the degree to which a process can be reconstructed into modules for parallel execution (Parraguez et al., 2019). Specifically, process modularity is to standardise manufacturing sub-processes to be re-sequenced easily or open inter-change for new modules’ ‘plug-and-play’ (Tu et al., 2004). Hence, there are few strong ties between process modules (i.e. sub-processes), which facilitates rapid decoupling and resequencing of processes (Fine et al., 2005).

Feitzinger and Lee (1997) propose three principles for process modularity, including (1) process standardisation, (2) process resequencing, and (3) process postponement. Firstly, process standardisation is the decomposition of a process into standard sub-processes. Then, process standardisation produces standard basic units and customises sub-processes of the base units shared by products. Secondly, process resequencing stands for reordering sub-processes to achieve the occurrence of standard sub-processes firstly and the occurrence of customisation sub-processes lastly. Thirdly, process postponement means postponing customisation sub-processes until a customer order is received or placing those sub-processes in distribution centres for maximum flexibility. In addition, there are two process dimensions (i.e. time and space) for defining the coupling between modules. Highly integral process architectures can be integrated with time and space at the same time. It is also possible to integrate process architectures in either time or space (Voordijk et al., 2006).

2.3.3 Supply chain modularity

The research of modularity in the supply chain is an emerging area (Salvador et al., 2002; Voordijk et al., 2006), and spreading in construction (Doran & Giannakis, 2011; Voordijk et al., 2006), automation (Doran, 2004; Doran et al., 2007; Ro et al., 2007) and many other industries. Flexible planning in decisions makes modularity to be a promising approach to deal with the uncertainty challenge caused by increased competition and market volatility (Bhosekar et al., 2021). The trend to modularise the supply chains facilitates the transformation and reorganisation of value creation within supply chains (Collins et al., 1997; Doran & Roome, 2003).

Supply chain modularity emphasises the interdependence within and independence across certain supply functions or tasks. Supply chain modularity refers to whether certain supply functions or tasks are conducted by a single supplier or not and whether they can be explicitly distinguished from others (Wolters, 2002), thus aiming to mitigate the complexity within supply chain coordination. Supply chain modularity focuses on the division of labour within a supply chain network for specific supply chain functions and tasks and how companies in the network interact with each other (Voordijk et al., 2006), which is for a relatively flexible and interchangeable relationship among suppliers, customers and partners (Fine et al., 2005).

By analogy with modular products and processes, a modular supply chain responds to the changing demands on functionality and performance of different supply chain variants by cultivating alternative capabilities to deal with different versions of functional components (Voordijk et al., 2006). In supply chain settings, modularity is the degree of non-proximity of elements, while integrity depends on the degree of proximity of elements (Voordijk et al., 2006). Fine et al. (2005) define the degree of proximity from four aspects: geographic proximity (i.e. physical distance), organisational proximity (i.e. ownership, managerial control and interpersonal and inter-team interdependencies), culture proximity (i.e. language, business mores, standards, and laws), and electronic proximity (i.e. intranets, video conferencing). Thus, a modular supply chain might involve 'geographically dispersed actors, each one characterized by autonomous managerial and ownership structures, diverse cultures and low electronic connectivity' (Salvador et al., 2004).

2.3.4 Organisational modularity

After the mid-1980, organisational modularity has become an emerging alternative supply chain choice for building a new vertical integration and market mechanism (Pires, 1998; Schilling & Steensma, 2001; Sturgeon, 2002). However, there is also no consensus on the definition of organisational modularity. By simply analogy with the idea of product modularity, organisational modularity seems to implicate an organisation is merely divisible into different parts for the accomplishment of specific tasks, which, however, is not a new claim in the organisation literature and cannot distinguish the modular organisation from other organisational structures (Benassi, 2009).

In addition, there is also no consensus on what 'organisational' mean. For example, some studies regard the occurrence of organisational modularity at a firm level (Brusoni, 2005;

Galunic & Eisenhardt, 2001; Quan, 2006). In contrast, with a mainly focus on the inter-firm level, a modular organisation is defined as a loosely coupled structure of development organisations autonomously and concurrently working together (Sanchez & Mahoney, 1996). Soyer et al. (2019) argue that it makes no sense to define organisational modularity by analogy with product modularity. Soyer et al. (2019) define organisational modularity as ‘A loosely coupled network of autonomously operating self-contained units, having a low level of interaction but a high level of awareness among each other through standard interfaces, which can be flexibly recombined into a variety of organisational configurations.’

Organisational modularity tries to explore various efficient and flexible solutions through decomposition. Heterogeneity increases between the internal organisational subcomponents and enhances external conditions and various opportunities for proper alignment (Eisenhardt & Brown, 1999; Schilling, 2000). Three characteristics have been identified by Schilling and Steensma (2001) and Ketchen Jr and Hult (2002) to construct organisational modularity: use of contract manufacturing, utilisation of external human resources, and establishment of alliances.

2.4 Relationships between multiple dimensions of modularity

2.4.1 Product and process modularity

The relationship between product modularity and process modularity accounts for most studies related to multi-dimensional modularity relationships. The implication of coupling the product and process modularity has been highlighted for its benefits in developing and managing various postponement solutions in product manufacturing (Forza et al., 2008). The impacts of their combination on production introduction performance (Vickery et al., 2016), supply disruption (Gualandris & Kalchschmidt, 2013), manufacturing agility and firm growth performance (Jacobs et al., 2011) have attracted lots of studies, some of which believe there is a strong relationship between product modularity and process modularity (Kusiak, 2002). For example, product modularity tends to have a considerable positive impact on process modularity in the best-fitting interactive mode, while product modularity and process modularity tend to be specified as independent exogenous constructs in the poorly fitting mode (Jacobs et al., 2011). The impact of the modular product on the process raises an issue related to an essential question proposed by Hayes (1979): must there be an alignment of structure and infrastructure to improve performance?

2.4.2 Product and organisational modularity

The relationship between organisational structure and product structures has been discussed for a long time. In 1967, Conway's law was established to describe that 'any organisation that designs a system (defined broadly) will produce a design whose structure is a copy of the organisation's communication structure' (Conway, 1968). Hereafter, the mirroring hypothesis continued the discussion of Conway's law and predicted that organisational ties within a project, firm, or group of firms (e.g., communication, collocation, employment) would correspond to the technical dependencies in work being performed (Colfer & Baldwin, 2016). Modular organisational forms, in which loosely coupled organisational units specialise in distinct knowledge domains, are more likely to design modular products (Sorkun & Furlan, 2017).

However, some studies also implicate that the relationship between them is far more complex than the speculation of the mirroring hypothesis (Brusoni & Prencipe, 2001). For example, some industries might have no obvious correlation, or the relationship might be negative (Tunisini, 2006; Worren et al., 2002). Some industries fall into a 'mirroring trap' (Colfer & Baldwin, 2016), hindering systems integration and project success. 'Mirroring trap' means professional knowledge is deeply rooted in the personal behaviour of professional companies and their employees (Hall et al., 2020), which traps project design and execution into the prevailing standard system architecture and resists attempts for system-level innovation

(Katila et al., 2018; Taylor & Levitt, 2007). Many recent studies have explored the company's strategic actions to achieve systems innovation and how integration strategies can make individual projects eliminate the 'mirroring trap'.

2.4.3 Product, process, and supply chain modularity

The supply chain is a promising facet to examine possible non-linear effects within the interaction with the product and process modularity (Jayaram & Vickery, 2018; Vickery et al., 2016). Some studies, such as Droge et al. (2012) and Jermsittiparsert et al. (2019), investigate the impact of supply chain integration on mediating the effects of product modularity and process modularity. Thus, in addition to product and process modularity, Fine et al. (2005) add a third perspective on modularity (i.e. supply chain modularity) and argue that these three perspectives tend to reinforce each other and be aligned along the integrity - modularity spectrum. In contrast, integral products tend to be developed and built by integral processes and supply chains.

Fine's three-dimensional modularity was established to claim that modular products tend to be designed and built by modular processes and supply chains (Fine et al., 2005). In specific industrial scenarios, Voordijk et al. (2006) evaluate the applicability of Fine's three - dimensional modularity concept and showed its capability in describing the modularity degree of certain products, processes and supply chains. However, Fine's three-dimensional concept needs to be refined to make up for the current shortcomings when analysing products, processes and supply chains, which shows that it is still relatively rough in nature (Voordijk et al., 2006).

2.5 Value of modularity in design

2.5.1 Complexity in design

An essential question in complexity science is: what is complexity? ‘Complex’ is combined by two Latin words, namely ‘com’ which means together, and ‘plectere’ which means to entwine. Complexity prevents human understanding by entwining many parts together. The exploration of complexity contributes to understanding modern engineering systems and designing those systems and artefacts in general (Maier & Fadel, 2006).

Complexity has been recognised in various design domains, such as urban design (Batty, 2009), building design (Leaman & Bordass, 1993), engineering design (ElMaraghy et al., 2012), and service design (Young, 2009). The complexity of design involves dynamic relationships and interactions between different stakeholders and between stakeholders with artefacts. Various individuals perform tasks span disciplines, companies, and locations, leading to an evolving network of interrelated activities (Wynn et al., 2005). Among multiple unrelated design decisions, there might be emerging unintended interactions which increase the complexity. Emphasizing on underdevelopment system and treating complexity in the functional domain rather than the physical domain, Suh (2005) defines complexity as ‘the measure of uncertainty in achieving the functional requirements of a system within their design ranges’ in the design-centric complexity theory, which differ from others that view regard complexity as an inherited and absolute character of existing systems.

With the design-centric complexity theory, complexity becomes a design consideration to be synthesised in situ, not analysed afterwards. In other words, complexity is not an ‘as-is’ description anymore, but rather a ‘to-achieve’ state, of a system of interest (Lu & Suh, 2009). However, the complexity of the design process remains an area where the complexity of process is not well understood or managed as physical products in the AEC industry (Austin et al., 2007).

2.5.2 Value of modularity in design

2.5.2.1 Modularity in design and intellectual property protection

Excessive exposure to design information leads to easier replication, which may risk the investment in design. Many strategies of modularity have been proposed for Intellectual Property (IP) protection. For example, when the design information is difficult to protect by the legal system, modularity can protect intellectual property by dispersing and hiding crucial information in the design into independent modules. Limiting the accessibility to system interfaces from third parties is another way of IP protection. Systems designers can achieve that by modularity-in-production without modularity-in-use (Baldwin & Henkel, 2015).

In addition, it is combining enforceable legal rights (patents, copyrights, legally-sanctioned trade secrets) and direct control of access to information (controlling who knows what) can manage the accessibility of knowledge embodied in modules (Henkel et al., 2013). In a modular structure, a company's strategy can locate core R&D activities such as architecture design, interface protocols, and some critical components in countries that are more likely to be protected by intellectual property legal systems, thereby preventing leakage and disclosure of critical information (Quan & Chesbrough, 2009).

However, many challenges still exist regarding the design for modularity IP. For example, some original equipment manufacturers adopt non-sustainable design strategies for modularity IP by reducing the ability to disassembly and reassembly (Kim et al., 2021). Third parties thus cannot reuse or replicate their state-of-the-art designs (Henkel et al., 2013; Krystofik et al., 2015). For product family designs, divergent commonality strategies are adopted in product family design to reduce the sharing of sensitive components and decrease reusability (Henkel et al., 2013; Rojas Arciniegas & Kim, 2012; Subramanian et al., 2013), which is in contradiction with sustainable design principles.

2.5.2.2 The option value of modularity in design

Modularity brings lots of benefits to designing, such as higher adaptability and evolvability (Baldwin et al., 2000; Garud & Kumaraswamy, 1995; Schilling, 2000; Simon, 1962). The relationship between complex system design and the manner in which the system evolves over time has been discussed in many studies. Design following modularity principles is relatively more evolvable for the ability of modularity in design to facilitate future adaptations without requiring specification in advance. It facilitates the process of modifying or updating the system's components to reflect changing conditions or circumstances. This feature is valuable to the degree that a system must meet various future requirements, the specifics of which cannot be predicted ex-ante (MacCormack et al, 2001). In such situations, one must 'design for uncertainty.' (MacCormack et al., 2007).

Modular design offer alternatives that non-modular ('interdependent') designs do not provide. Specifically, in the hidden modules, designers may replace early, inferior solutions with later, superior solutions. Such alternatives can be modelled as 'real options' (Baldwin & Clark, 2002). In essence, modularity creates options and, 'option value' with respect to new and improved designs, which is particularly important when a system must meet uncertain future demands (MacCormack et al., 2007), and real options theory offers a natural framework to evaluate a modular design (Gamba & Fusari, 2009).

2.6 Modularity in construction

2.6.1 Complexity in building systems integration

2.6.1.1 Systems integration

A system is a connected collection of interrelated and interdependent parts; a complex whole that may be more than the sum of its parts. A system is influenced by its environment, defined by its structure and purpose, and expressed through its function. From simple, closed, and well-defined systems, such as aeroplanes, to complex, open, and dynamic systems, such as the Internet, the definition of ‘system’ has evolved over the years.

Originating from military-based engineering in the 1940s, systems integration has been spread into various industries as a significant modern-day strategic capability. In engineering, systems integration can be defined as a process of efficient composition of components/sub-systems into one whole system. It aims to deliver the overarching functionality through aggregating sub-systems cooperation (Madni & Sievers, 2014).

Many types of integration exist, such as vertical, horizontal, star, and industrial lifecycle integration. The main focus of systems integrations is interoperability which refers to the ability to deal with heterogeneous data from various systems. Organisations tend to achieve strong interoperability for systems integration by performing compatible solutions on exchanged information.

However, different systems may have various exchange preferences for data interoperation solutions. The achievement of forming a coherent whole from sub-systems encounters many challenges, including the trust for data sharing, willingness to outsource, the ability to communicate and the cost of integration, which creates hurdles of preventing or slowing down systems integration within and among systems. Invariably, interfaces are the weakest part, leading to systems integration failure. Specifically, the interface’s incomplete, inconsistent or misunderstood specification is usually the root cause of failures (Madni & Sievers, 2014).

2.6.1.2 Building systems

According to RIBA (2021), the building system is defined as ‘the constituent parts of a building, including, but not limited to, structural systems, mechanical and electrical systems, façade, ceiling, floors and wall systems’. The building system is a set of interrelated and interconnected elements providing foundations for the designed performance of a building.

On a broader level, building systems involve technological and managerial procedures for manufacturing and assembling these elements for designed purposes (Warszawski, 2003).

There are many ways to classify building systems based on the particular interest of stakeholders. For example, focusing on construction technology and main structural and space-enclosing material, building systems can be distinguished into four major groups 1) timber, 2) steel, 3) cast in situ concrete, and 4) precast concrete. Building systems also can be classified according to the critical systems of the facility, such as the electrical, Heating, Ventilation, and Air Conditioning (HVAC), security, life safety, and lighting, which are rarely, if ever, independent entities. These systems depend on each other for operation. All building systems are typically designed, installed, managed, maintained and supported by expert teams. They are often evaluated and controlled both as an independent system and as a part of a larger system and the whole building. Thus, a building can be understood as a complex technical-social-ecological system.

2.6.1.3 Building systems integration

This research regards building systems integration as a process of bringing together all building components physically and functionally into a coordinated whole. Many aspects, including the multiple stages of the building life cycle, the integration of multidisciplinary teams, and the use of heterogeneous software and hardware systems/tools, influence the complex nature of the building process.

Building systems integration is from two main dimensions: software integration for the design process and hardware integration for physical components (Bachman, 2004). Integrating systems at the level of the building process and the final building product is an important prerequisite for realising various interrelated building functions. Building systems integration regards the building as a whole of a group of integrated/interdependent systems rather than as many independent building sub-systems. In addition, a part within a building system usually has more than one function and defies simple generic classification. It would not be easy to call out distinct systems when a building is highly unified, as separate systems have converged to achieve multiple performance goals by utilising a singular element. Besides, building systems integration involves two aspects, namely the iteration between integration (how the parts or components work together) and division (how the parts or components are defined and built) (Whyte, 2016).

Systems integration does not mean an integrated product. Both integrated products and modular products are two ways to achieve systems integration in construction. The interaction among the various building service systems, and between the systems and the building structure provide the environment and means for optimal utilisation of the building (Arkin & Paciuk, 1997). Integrating these systems into the building internally at an early stage of design would save costs and prevent time-consuming modifications (Abdelhameed & Saputra, 2020).

Whyte (2016) categorises systems integration into three overlapping strands: innovation, complex projects and engineering design. The challenge is that different disciplines use different rhetoric and terminology to develop systems integration. This research extended the work of Bachman (2004), who classifies building systems integration in architecture into two aspects: the hardware of integration (i.e. building components) and the software of integration (i.e. design processes). This research reclassified the three overlapping strands (Whyte, 2016) and two modes of integration (Bachman, 2004) into four dimensions with clear boundaries.

This research aligns with Emmitt (2014) on the significance of a design organisation's impact on how individual projects are developed. The categorisation of hardware of integration is unchanged, but two additional aspects of software of integration, design organisations and supply chains are added. The four dimensions of building systems integration (building components, design process, design organisations, and supply chains) correspond to the four dimensions of modularity (product modularity, process modularity, organisational modularity and supply chain modularity). This is the foundation upon which further understanding of building systems integration through modularity can be built.

Recent authors have mostly examined complexity from either the design aspect, such as Fronczek-Munter (2016), Mills et al. (2015), and Verderber (2010), or the construction aspect, such as Lavy and Fernández-Solis (2010) and Schönbeck et al. (2020). This research focused on the complexity at the interface between design and construction, that is, the complexity of DfMA in healthcare construction. This research emphasises the necessity to reduce complexity in order to achieve building systems integration. This research tries to extend the current understanding and knowledge of the complexity of design in healthcare construction and healthcare building systems and the relationship between the design and construction stages.

2.6.2 Modularity theory in the AEC industry

2.7.2.1 Technical perspective of modularity

The modularity-related research in the AEC industry mainly has two completely different directions. In the AEC industry, modularity usually refers to modular construction. From this perspective, the research of modularity in construction focuses on physical building component-based integration to modules. The meaning of modular construction sometimes appears in the literature and practices through some interchangeable terms, such as ‘prefabrication’, ‘industrialised construction’, ‘off-site manufacture’, ‘manufactured construction’, ‘modular integrated construction’, and ‘modern methods of construction’ (Arif & Egbu, 2010), although there are specific differences among them. This research uses OSC throughout the research to keep consistency, and regards it as a typically perceived measure of product modularity in the AEC industry.

The term OSC refers to the process of manufacturing and preassembly elements or components of a construction project at a location different from the installation location and usually consists of planning, design, manufacturing, and assembly in purpose-built factories (Goodier & Gibb, 2007; Hosseini et al., 2018; Jin et al., 2018; Pan et al., 2007; Smith & Quale, 2017). Building components fabricated in controlled factory environments are then transported to construction sites for manual or automatic assembly (Jin et al., 2018). The off-site location can be permanent manufacturing facilities or ‘flying factories’ which serve a temporary duration for one project and can be ‘fly’ to a new location for another project (Couper et al., 2019; Dowsett et al., 2017). Among the many forms of OSC, a common and typical feature is that construction projects are based on factory or factory-like conditions (Jiang et al., 2018). These forms of OSC favour repetitive components and a factory-based environment for construction products.

OSC is regarded as a promising approach with capabilities in production safety, economies of scale and sustainability to overcome construction challenges and transform the industry (Abanda et al., 2017; Jiang et al., 2018). However, many OSC challenges and implementation difficulties still exist, such as high initial set-up costs, immature techniques, and a lack of skilled labourers (Arif et al., 2012; Gan et al., 2018; Mao et al., 2015; Pan & Sidwell, 2011). Pan et al. (2023) illustrate the intricate relationships and complexities of problematic interfaces in OSC. Besides, in traditional building design, designers do not need to consider too many manufacturing and construction issues. Due to the weak fault tolerance of OSC, the design will have a huge impact on the cost and quality of the project. Therefore, designers must be familiar with the industrial supply chains and establish systematic design thinking throughout the process. Research in this field has been explored for decades and dominates the majority of modularity studies in construction.

2.7.2.2 Social-technical perspective of modularity

The other is from the social-technical perspective of modularity. More than a functional process to ensure that the components of a system are stuck together efficiently and sustainably, modular construction is a means of operating processes that drive the system in an efficient manner (Batty, 2009). Flyvbjerg (2021) emphasises the impact of scaling modularity on successful megaprojects and the key identification of LEGO (i.e. the replicable and modularizable units) in projects. The research on modular projects is not new in the AEC industry. More than 20 years ago, Phillips et al. (1999) develop the concept of modular projects, whereas relatively few studies were generated after that. Although the modular organisation is a hot topic in the general management study, the project as a temporary organisation (Lundin & Söderholm, 1995; Turner & Müller, 2003) proposes unique settings and situations for incorporating the modular concept, which means the modularity in projects would be different from the ordinary organisation process.

Furthermore, Doran and Giannakis (2011) investigate the modular supply chain in construction. Besides the organisation level, the modular concept can also be achieved through the process level. For example, the design structure matrix was introduced as a modular decomposition method for the design process (Eppinger & Browning, 2012). By this method, design tasks can be aggregated into different modules according to their interrelationships and independence.

However, in the AEC industry, there are rarely existing studies about process modularity. As most studies related to process modularity are from the manufacturing industry, the uniqueness of the AEC industry may make some attributes, relationships, or effects of process modularity not work in architectural practices. In addition, buildings, as a one-off product manufactured by a temporary organisation, may increase or decrease the importance of certain principles of process modularity, as the scale effects of cross-project/product may be challenging to be achieved in many cases. Thus, more evidence is required to test the concept and theory of process modularity.

In addition, academia has not fully addressed the relationships between physical modules, modular organisation, modular process, and modular supply chain in the AEC industry. A few have investigated the concept of product modularity (Chauhan et al., 2022; Da Rocha & El Ghoz, 2019; Da Rocha & Koskela, 2020; Eriksson et al., 2021). However, these studies all adopted a single dimension of modularity without considering other perspectives.

Only limited studies focus on the multi-dimensional modularity within the context of the AEC industry. For example, Hall et al. (2020) investigate the mirroring hypothesis at the construction firm level. Voordijk et al. (2006) also examine Fine's three-dimensional modularity at the construction firm level. In other words, a few strategies of product modularity are generated based on the relationships among the multi-dimensional modularity. Understanding the relationship between multiple dimensions of modularity can contribute to achieving modularity as a whole. The lack of relevant research makes the current focus more on the design and implementation of modularity at a single dimension, such as product modularity. However, these implementations of product modularity cannot be separated from the context (i.e. process and supply chain) and the support of the context. Implementing the single dimension of the modularity principle proposed in research, such as some of the guidelines in the construction-oriented DfMA, may not work.

2.7 Chapter summary

This chapter focuses on modularity theory as a universal strategy for reducing complexity that promises to be applied to the AEC industry to understand emerging issues and drive innovation in design value and building systems integration. In the next section, this research addresses the scientific progress of DfMA in construction, a design philosophy that is to be understood, integrated and empowered using modularity theory.

Chapter 3 Design for Manufacture and Assembly

3.1 Introduction

This chapter provides a workable definition of DfMA within the context of current practice, incorporating a construction-oriented background. The chapter begins with a review of the many DfMA-related terms and their definitions in the literature, revealing the contextual issues associated with them. The chapter also provides a literature review of the development of digital-enabled design, mainly covering the sections of digital-enabled DfMA and BIM-based design in healthcare construction. A discussion of the prospects and challenges of DfMA follows this.

3.2 Defining DfMA

DfMA is both a design philosophy and methodology whereby considers the downstream processes of manufacturing and assembly when designing products (Boothroyd, 2005). Originating from the manufacturing industry, DfMA suggests a systematic design process that integrates the production experience into the product design (Corbett, 1991; Harik & Sahmrani, 2010; Kuo et al., 2001). It has two components: Design for Manufacture (DfM) and Design for Assembly (DfA). DfM compares selected materials and manufacturing processes for the parts, determines the cost impact of those materials and processes, and finds the most efficient use of the component design (Ashley, 1995), while DfA addresses the means of assembling the parts (Bogue, 2012).

Altogether, DfMA represents a shift from a traditional, sequential approach to a non-linear, reiterative design methodology. Since its emergence during World War II and flourishing in the 1960s~1970s, numerous DfMA guidelines, such as Boothroyd (2005), Swift and Brown (2003), Bogue (2012), and Emmatty and Sarmah (2012), have been developed to help designers to operate this design philosophy to improve designs, productivity and profitability (Gatenby & Foo, 1990; Kuo et al., 2001). More recently, a Design for Excellence (DfX) approach has developed where the 'X' may denote excellence in any aspect, including testability, compliance, reliability, manufacturability, inspection, variability, and cost (Eastman, 2012; Maskell, 1991).

DfMA is now beginning to come into vogue in the AEC industry. Notably, the RIBA published a series of DfMA overlays to its *Plan of Work 2013* and *2021*, respectively. The UK, Singapore, and Hong Kong governments have published DfMA guides or emphasised their importance in construction. Industry giants such as O'Rourke (2013) and Balfour Beatty (2018) have even indicated they consider DfMA to be the future of construction. Before elaborating on this background, some terminology needs to be clarified.

According to Dainty et al. (2007), precisely what constitutes construction is subject to a range of boundary definitions. There are narrow and broad definitions of construction (D. Pearce, 2003). The narrow definition of construction focuses on onsite assembly and the repair of buildings and infrastructure. Contrastingly, the broad definition of construction could include quarrying of raw materials, manufacture of building materials, sale of construction products (Dainty et al., 2007), and professional services such as architectural design, urban planning, landscape architecture, engineering design, surveying, construction-related accountancy, and legal services (Jewell et al., 2014). All the above sub-sectors can be allocated a four-digit U.S. SIC (Standard Industrial Classification) code in accordance with the United Nation's International SIC or the U.K. SIC (Lu et al., 2013).

At the risk of oversimplification, this research treats upstream architecture and engineering activities as 'design', and downstream onsite activities as 'construction'. Onsite construction is traditionally conducted using cast in-situ; it is a combination of fabrication and assembly

(Ballard & Howell, 1998). However, in recent years, we have seen a number of initiatives to minimise onsite construction, shifting to downstream offsite manufacture/fabrication brought back onsite for assembly. To understand the concept of DfMA in construction, one must position it in the heterogeneous context of construction and be cognizant of the relationships between architecture, engineering, construction, manufacturing, and assembly therein.

One can also understand the DfMA trend against the background of global construction, which is characterized by ever-heightened product sophistication, sluggish productivity growth, the increasing influence of cross-sectoral learning, and emerging technological advancements in virtual design and construction. Production inefficiency in construction has been criticized in a succession of influential UK-based industry reports, including ‘Constructing the Team’ (Latham, 1994), ‘Rethinking Construction’ (Egan, 2002), ‘Never Waste a Good Crisis’ (Wolstenholme et al., 2009), and more recently in The Economist (2017) comparing construction productivity with its manufacturing and agriculture counterparts. Construction has been accused of being ‘adversarial’, ‘ineffective’, ‘fragmented’, and ‘incapable of delivering’, with appalling backwardness that should be improved from within, e.g., through industrial structure or organisational culture. Increasingly, it is exhorted that construction should look to and learn from highly productive industries such as advanced manufacturing (Camacho et al., 2018).

The exploration of production innovation, in particular OSC, has provided an unprecedented opportunity for DfMA. The similarities between OSC /prefabrication and manufacturing have pushed DfMA to the fore of the industry’s cross-sectoral learning and innovation agenda. In addition, emerging technological advancements, such as BIM, 3D printing, the Internet of Things (IoTs), and robotics, provide new AEC industry entry points for manufacturing knowledge, and DfMA in particular, for efficiency improvement.

However, current DfMA practices in construction still, by and large, follow DfMA guidelines developed in a manufacturing context without sufficiently considering the differences between construction and manufacturing. For example, DfMA procedures in Boothroyd (2005) consider DfA and DfM but not the logistics and supply chain, which plays a critical role in offsite prefabrication construction. Some construction DfMA guidelines, e.g., Gbadamosi et al. (2019), M.-K. Kim et al. (2016), and Banks et al. (2018), originate more or less from manufacturing-oriented guidelines. While inspiring, some of these guidelines are not necessarily a good fit with the AEC industry characteristics, leading to an inability to improve manufacturing and assembly. Some guidelines are proposed in a fragmented fashion and do not form an organic whole, leading to a lack of comprehensive, easy-to-use references throughout the building process. Following RIBA's vision (2021), much 'soft-landing' work remains to implement DfMA in construction.

When looking at the history of DfMA in construction, scholars often cite the pioneering modernist architect Le Corbusier who advocates the industrialisation of construction in his influential book Towards a New Architecture (1923) and proposes the famous maxim, 'A house is a machine to live in'. However, the popularity of DfMA in construction is a recent phenomenon. Unlike manufactured products designed in-house, mass-produced, and sold to end users, construction products (e.g., housing, buildings, and infrastructure) are bespoke (Fox et al., 2001). Every construction product is contextualized within the geotechnical conditions of the site and its surroundings, the planned socio-economic function, and many other factors. There can be no 'standard', 'one-size-fit-for-all' design for mass production. It would be exceedingly difficult, if not impossible, for architects, like their counterparts in manufacturing, to conceptualize, optimise, prototype, and select a design to mass construct. In addition, the orthodoxy dislikes the tedium of 'standard' architecture design. Thus, the 'one-off' project as an organisational form has been adopted in the AEC industry to organise work (Wang et al., 2018). Simply put, the AEC industry is engaged in projects, while other industries are concerned with products.

While construction materializes our built environment and is linked to cultural identity and civic pride (D. W. Pearce, 2003), it has long been criticized for its nuisance and poor quality (Baloi & Price, 2003), and recently, alleged low productivity (Groves, 2017). Cross-sectoral learning has been exhorted for construction (Kao et al., 2009). The AEC industry has been reinventing itself through production theory (Koskela, 1992), especially through the integration of design, manufacture, and assembly (Bridgewater, 1993) and lean concepts and tools for making site assembly more efficient (Tommelein, 1998). In the 2010s, government and industry documents began to include DfMA in their development plans and to illustrate its detailed definition and application in the industry. In these plans, DfMA is advocated to combine architectural design, manufacturing and on-site installation organically. The introduction of DfMA to the AEC industry can be understood against this cross-sectoral learning and transformation background.

3.3 Digital-enabled DfMA in healthcare construction

3.3.1 BIM and design optimisation through DfMA

3.3.1.1 DfMA as a design optimisation method

Table 1 shows the 11 articles related to DfMA optimisation methods and the evaluation of engineering choices or alternatives during design. Significant in this state-of-the-art review is DfMA's use for building façades (Azzi et al., 2011; Başarır & Altun, 2018; Di Giuda et al., 2019; Montali et al., 2018; Montali et al., 2019), weatherproof seals (Orlowski et al., 2018), and modular components (Rausch et al., 2017). Few studies focus on design optimisation of the whole built project, although some, such as Yuan et al. (2018), establish a process information model for DfMA-oriented prefabricated buildings. While Gerth et al. (2013) combine DfMA, constructability and waste management for the purposes of optimisation of housing design.

Table 1 Optimisation methods based on DfMA Since 2009

Name	Knowledge Elicitation Methods	Data Analysis	Focus		Domains	Ref.
			DfM	DfA		
BIM-Based optimiser	Literature review and questionnaire	Voting-Analytic Hierarchy Process		✓	Building elements and materials	Gbadamosi et al. (2018)
Design for Construction	Workshop	Logical argumentation		✓	Housing wall	Gerth et al. (2013)
Knowledge-based engineering	Literature review and interview	N/A	✓		Façade	Montali et al. (2018)
Knowledge-rich optimisation	Semi-structured interview	N/A	✓		Façade	Montali et al. (2019)
DfMA-based evaluation	Questionnaire, interview and observation	Analytic Hierarchy Process	✓	✓	Bridge	Safaa et al. (2019)
BIM-based Approach to Façade Cladding Optimisation	Project owners	Multi-criteria methodology	✓		Façade	Di Giuda et al. (2019)
DFMA-oriented prefabricated building information model optimisation	Expert consultation	N/A	✓	✓	Prefabricated building	Yuan et al. (2018)
Optimum assembly planning	3D imaging (laser scanning)	Proposed Algorithm	✓	✓	Modular component	Rausch et al. (2017)

Variability-oriented assembly system	Project dataset, interview and site survey	Complete-linkage clustering		✓	Façade	Azzi et al. (2011)
Methodological approach to Design and Development of waterproof seals	Expert consultation	N/A	✓	✓	Weatherproof seals	Orlowski et al. (2018)
Redesign procedure to manufacture adaptive façades	Designers and experts	Weighted decision matrix method	✓	✓	Façade	Başarır and Altun (2018)

Optimising design almost always involves a design trade-off as it needs to consider numerous criteria. The vast majority of these studies used the multi-criteria methodology. Most are designed to simplify data acquisition. For example, applying Analytic Hierarchy Process (AHP) or an evolutionary method based on AHP, such as Voting-AHP, is the way to apply a criteria weighting. Root cause analysis and cause and effect analysis were also used as the basis of weights (Gerth et al., 2013). A partial limitation of all these methods is the process of subjectively assigning relevance and weighting to assessment criteria. What is more, weighting judgements may vary from project to project and may depend on different domain knowledge.

Optimisation algorithms are also applied to the design process to judge potential alternatives. For example, Rausch et al. (2017) propose an algorithm to optimally plan, order and arrange components and assess geometric variability and rework. Montali et al. (2019) create a 'meta-domain' of analysis to find trade-offs between performance and architectural intent while allowing maximum compliance with manufacturing, logistic and design constraints.

Manufactured products, such as specific modular components or facades, have been optimised using this method, but rarely whole architectural building solutions.

3.3.1.2 Digital-enabled DfMA for design optimisation

BIM, as a typical digital-enabled approach, can potentially extend the innovative and collaborative use of DfMA at both the object and integrated collaborative environment levels. Table 2 shows those that have applied BIM and DfMA. Some integrated BIM, DfMA processes and strategies for implementation. For example, Machado et al. (2016) establish BIM-based collaborative strategy for DfMA, while Yuan et al. (2018), Kremer (2018) and Samarasinghe et al. (2016) integrate BIM into the design process.

Table 2 BIM-based DfMA

Authors	**BIM application in DfMA**
Yuan et al. (2018)	Integrate BIM in design process
Rausch et al. (2017)	Collect geometric data and identify critical points for the assembly from BIM model
Gbadamosi et al. (2018)	Collect geometric data and material information from BIM model
Machado et al. (2016)	Establish BIM-based collaborative strategy
Kremer (2018)	Integrate BIM in design process
Lee et al. (2014)	Use BIM tool to process data
Tresidder and White (2018)	Use BIM to develop a checking and review tool
Di Giuda et al. (2019)	Collect geometrical information from BIM model, and process data using BIM plug-in
Samarasinghe et al. (2016)	Integrate BIM in design process

BIM provides an effective tool for review, checking, and data processing (Di Giuda et al., 2019; Lee et al., 2014; Tresidder & White, 2018). Open Application Programming Interfaces (APIs) can support BIM software vendors and help third-party developers to program advanced software modules for the specialized information process service (Lee et al., 2014). BIM, digital DfMA models, components and connections can be used to streamline the processes of manufacture and assemble. Data-rich models and standardised DfMA elements, such as prefabricated prefinished volumetric construction, prefabricated bathroom unit, and precast components, can support adopting a more systematic digital-enabled DfMA process. Figure 9 shows potential BIM actions for DfMA that require further research and development.

	Stages	Key BIM for DfMA Actions			
1	Project Brief Development	Build massing studies (e.g. orientation, area, volume etc.) based on site constraints and client and authorities' requirements)	Capture rules for DfMA adoption (e.g. modular floor heights, grid dimensions etc.)	Develop DfMA&BIM implmenetation strategies and incorporate into BEP and project design	
2	Concept Design Development	Develop parametric "placeholder" objects for spaces with modular grids&layouts	Use space objects to generate multiple options to find 'best' fit to project brief	Generate room data sheets from space objects for approval of functional, environmental and finishes requirements	Use models to show concept for stakeholders' feedback and approvals
3	Detailed Design Development	Add in more details to space objects-geometry and data in detailed 3D models	Use objective analysis and reporting tools to demonstrate that brief objectives are achieved	Validate DfMA solutions through early contractor and supply chain engagement	Generate detailed part and whole models for different disciplines for early coordination
4	Pre-Construction	Refine models to incorporate inputs from DfMA supply chain	Develop overall construction programme schedule and sequencing	Develop fabrication&installation sequences, method statements, resource management plan etc.	Generate digital prototypes to verify construction strategy
5	Construction	Generate shop drawings for fabrication from models/integrate fabrication with models	Track construction activities&resources based on planned programme and planned assembly sequence	Validate installation on-site and update models accordingly	
6	Post Completion	Ensure the as-built models are up-to-date for hand-over	Integrate as-built models with FM system		

Figure 9 Key BIM for DfMA actions (BCA, 2016)

3.3.2 BIM-based design in healthcare construction

3.3.2.1 Emerging BIM techniques for healthcare construction

In the current research, there are two major topics of BIM research in healthcare construction: 1) understanding the BIM adoption and implementation in healthcare construction; and 2) developing BIM-based techniques for various stages of healthcare construction, such as design, construction, and operation. Emerging BIM techniques for healthcare design and construction include functionalities embodied in BIM and new BIM-based techniques. Pikas et al. (2011) summarise 12 BIM functionalities in healthcare construction through multiple case analyses, including visualisation of form, model changes tracking, predictive analysis of performance, automated generation of drawings and documents, modelling temporary structures (scaffolding) and existing structures, automated clash checking, online communication of product and process information, online meeting sessions, reuse of model information, site planning, 4D and 5D schedule, information for survey and scanning systems, project status tracking, and as-built model. Their research indicates that BIM enables a holistic view of project delivery and helps integrate project parties into a collaborative process.

Furthermore, some studies developed BIM-based techniques and approaches to optimise the use of these BIM functionalities. Design science research was the most popular methodological approach adopted in this topic. As shown in Table 3, Oh et al. (2015) propose an integrated design system for BIM-based collaborative design and tested it by using a hospital building design. Lin et al. (2018) integrate BIM- game engine and VR technologies for healthcare design. Caixeta and Fabricio (2021) developed a physical-digital model to involve users in the design process for co-design in healthcare facilities. Peng et al. (2020) propose a BIM-based digital twin method for hospital construction in the construction stage. Baldauf et al. (2021) propose a process-based approach for client requirements management in healthcare design. Tutt et al. (2013) develop 3D immersive environments for client engagement practices in hospital design.

Many studies in the design stage focus on collaboration improvement by involving either clients or multi-disciplinary professionals by proposing BIM-based frameworks or workflows. These proposed techniques might be useful in specific project settings. However, with the changing of country context, construction method, project delivery method and procurement method, most of these proposed techniques cannot be used as one-for-all solutions. For example, with the introduction of OSC, the design and construction process of healthcare facilities would be totally changed. Tan et al. (2019) have identified that the barriers, challenges and strategies of BIM implementation would be different when comparing OSC and on-site construction. However, previous studies of healthcare construction ignored the impact of different construction methods on digital applications. No research addresses these issues by proposing corresponding digital-enabled techniques for DfMA in healthcare construction.

Table 3 BIM-based techniques for healthcare design

Author	Aims	Pilot case
Lather et al. (2020)	Automatic generation of near-optimal options of hospital layout	A university hospital in Porto Alegre, Brazil
Baldauf et al. (2021)	Process-based approach for client requirements management	Name unknown
Lin et al. (2018)	Data-based supported VR/BIM-based communication and simulation system	A cancer centre in Taiwan
Caixeta and Fabricio (2021)	Physical-digital model for co-design	A controlled experiment
Soliman-Junior et al. (2021)	Automated compliance checking in healthcare building design	A primary healthcare centre in West Midlands
Tutt et al. (2013)	3D immersive environments for client engagement practices in hospital design	A NHS hospital

Current studies mostly examine the implementation of BIM in healthcare construction from either the design aspect, such as the work by Merschbrock and Munkvold (2015) and Merschbrock et al. (2018), or from the construction aspect, such as the work by Love and Ika (2021), Davies and Harty (2013), Li et al. (2021), Harty et al. (2010), and Kokkonen and Alin (2016). The existing literature tends to take a reductionist view regarding BIM research. That is, if healthcare facility design and construction is viewed as a process of building a complex system (i.e., a hospital), these studies attempt to single out parts of the overall system, i.e., a particular sub-system, in the research of BIM technology. This approach does have specific benefits, for example, by reducing the complexity of the technology in the overall scenario. The disadvantage of this approach is the risk of hindering the application of BIM. Fragments or small snapshots of implementation prohibit the understanding of a whole system, whole project, full process approach to the implementation of BIM. This research focuses on the implementation of BIM at the interface between design and construction. This shift in focus attempts to transform separate studies on design and construction into a coherent and integrated process, which is more conducive to understanding how to facilitate building systems integration in healthcare starting from the design phase.

3.3.2.2 Understanding the implementation of BIM in healthcare construction

BIM is regarded as a set of practices or activities and a new way to work that emerges through the implementation process, rather than just a set of technologies. Thus, in addition to the above section mentioned digital-enabled techniques for healthcare construction, some studies have tried to understand the practices, activities, and implementation process of BIM. The case study method is widely used in this exploration, including single case and multiple case. As shown in Table 4, various studies have analysed BIM from different country backgrounds (e.g. Netherlands, Norway, United Kingdom, United States, Australia, etc.), building stages (e.g. design, construction) and theoretical background (e.g. diffusion of innovations theory, organisational discontinuity theory, sense-making theory, social network theory, etc.).

Table 4 Research of BIM adoption and use in hospital projects

Author	Case location	Case number	Use stage of BIM	Theoretical Background
Sebastian (2011)	Netherlands	2 (University Medical Centre St Radboud; Maxima Medical Centre)	Design and construction	N/A
Merschbrock and Munkvold (2015)	Norway	1 (name unknown)	Design	Diffusion of innovations theory
Mignone et al. (2016)	Australia	1 (The New Royal Adelaide Hospital)	Design and construction	Organisational discontinuity theory

Love and Ika (2021)	Australia	3 (Fiona Stanley Hospital; Perth Children's Hospital; The New Royal Adelaide Hospital)	Construction	Sense-making theory
Davies and Harty (2013)	United Kingdom	1 (name unknown)	Construction	N/A
Merschbrock et al. (2018)	Norway+Australia	2 (the new Østfold Sykehus Hospital, The New Royal Adelaide Hospital)	Design	Extended Leavitt sociotechnical model
Li et al. (2021)	China	1 (Jiangsu Maternal and Children Health Hospital)	Construction	Social network theory
Harty et al. (2010)	United Kingdom	2 (the Saint Bartholomew Hospital, the Royal London Hospital)	Construction	N/A
Kokkonen and Alin (2016)	United States	1 (name unknown)	Construction	Deconstruction and reconstruction theory
Pikas et al. (2011)	United Kingdom and United States	12 (Camnino Group Medical Building, Sutter Medical Castro Valley, Phoenix Children's Hospital, Maryland General Hospital, The Kaiser Permanente Oakland Medical Centre, Saint Bartholomew's and Royal London Hospital, Ann & Robert H. Lurie Children's Hospital, Good Samaritan Hospital, Sherman Replacement Hospital, Middle Tennessee Medical Centre, Las Vegas Hospital & Community Living Centre, Maple Grove Hospital)	Design and construction	N/A

However, healthcare projects were mostly used as a typical example of high-complexity building to explore the BIM adoption and implementation. Although many studies emphasised the complex and unique characteristics of healthcare construction compared with other building types, such as simple office or housing construction, many of these studies did not distinguish healthcare construction from others. For example, Harty et al. (2010) investigated the adoption and utilisation of BIM through two UK-based hospital projects. Kokkonen and Alin (2016) explore how practitioners are actively involved in a change through reflective learning when implementing BIM through a US-based hospital project. Li et al. (2021) study BIM’s formal and informal collaborative networks in traditional procurement through a China-based hospital project. Healthcare construction do can represent as one of the most complex building types, but it is still important to focus on healthcare construction alone to investigate its unique and similar context, challenges, and implementation scenarios. Healthcare facilities can be regarded as a complex building type to understand the implementation of BIM, but the unique functional and spatial requirements make BIM research specifically for healthcare building types urgently needed.

The second gap is the difference between BIM adoption and implementation in various building stages. Although the team and disciplinary integration among different companies of a project are always necessary in the literature, the collaboration between different stakeholders in projects is always fragmented. It cannot be denied that the adoption and implementation of BIM for different stakeholders, such as design institutes, contractors, suppliers, and facility users, would be totally different. Their different roles of them have an impact on their utilisation of BIM and also other digital-enabled approaches. It can be observed that some studies have clear identification about the exploration stage of BIM. For example, Merschbrock and Munkvold (2015) study the hospital’s BIM implementation of effective digital collaboration in the design stage. Davies and Harty (2013) investigate the ‘Site BIM’ in the hospital’s construction stage. However, there is no study to explore the impact of design on manufacturing and assembly.

3.4 Future potential for DfMA

3.4.1 Prospects of DfMA

DfMA is expected to have a wide range of applications, from one-off small-scale to large-scale construction projects, and can benefit both cast in-situ and OSC methods. However, its most widespread adoption is foreseen in OSC projects. Some empirical studies have begun to investigate the process of using DfMA guidelines for OSC. DfMA-oriented designs have been reported in various types of OSC projects around the globe. DfMA has also been applied to OSC using advanced digital-enabled approaches such BIM (Yuan et al., 2018). Although focusing on different scenarios, these studies share some common practices in applying DfMA guidelines, e.g., forming a DfMA-oriented design team by including architects, engineers, manufacturers and contractors, identifying design problems that need to be tackled for ease of manufacture and assembly, and optimising building design using DfMA principles.

The popularity of DfMA will increase with increasing demand for more integrated approaches of project delivery and value creation. The collaboration of stakeholders, such as designers, engineers, suppliers, and contractors at the early design stage means that more detailed information becomes available earlier than in the traditional design process. Such collaboration thus can help identify and address potential risks in the manufacturing and construction stages based on DfMA principles.

Another trend is the integration of DfMA and digital-enabled approaches like BIM. A building information model is the digital representation of a building with all building components represented by parametric objects (Eastman et al., 2011). BIM can facilitate DfMA implementation from two perspectives. First, DfMA requires an analysis platform for identifying opportunities for improving manufacturing and assembly processes through the design. BIM provides such a platform because BIM objects can have rich information on the actual building components. The information can be used to analyse how the components will be produced and constructed, and whether DfMA principles can be applied to make the design more appropriate for production and construction. Secondly, BIM enables a seamless collaboration environment. Designers, engineers, suppliers, and constructors can use the digital model to exchange ideas and share knowledge with each other (Chen et al., 2018; Zhong et al., 2017). After the design is consolidated, the BIM model can be directly sent to the suppliers or manufacturers for mass production.

To sum up, DfMA is expected to be adopted in the AEC industry to improve the project delivery's efficiency and effectiveness. Smooth deployment of DfMA principles in construction projects can be achieved with the support of new project management and delivery methods and digital-enabled approaches (e.g., BIM).

3.4.2 Challenges ahead

The first challenge facing DfMA application in construction is the lack of a suitable digital-enabled ecosystem that enables widespread adoption. An ecosystem includes guidelines, standards, and affordable technologies. Guidelines and standards are important for stakeholders, especially those with less experience, to govern the procedures of DfMA applications. Additionally, a report published by O’Rourke (2013) indicates that the gross capital cost of DfMA assembly, at the early adoption stage, is comparable to that of traditional construction methods. However, if new technologies were required to support DfMA applications, extra investment might be needed, making DfMA less competitive. These challenges necessitate a robust ecosystem enabling wide acceptance of digital-enabled DfMA.

Another challenge is associated with the new processes brought about by digital-enabled DfMA applications. DfMA requires stakeholders to shift their paradigm from conventional means of design, production, and construction (Chen & Lu, 2018; Gao et al., 2020; Yuan et al., 2018). However, it is not always easy for stakeholders to adjust to new processes. For example, designers might not be willing to accept manufacturing or construction input in their designs. The resistance to change could be considerably overwhelming. Therefore, additional efforts are necessary to manage the change, for instance, by increasing stakeholder awareness of the advantages of digital-enabled DfMA.

Furthermore, there are few cases of digital-enabled DfMA application in actual projects, perhaps owing to insufficient hands-on training and re-training arranged for different stakeholders to implement DfMA. Some stakeholders might choose to wait and see whether competitors implementing DfMA can receive actual benefits. Currently, a few large companies have begun to use DfMA in their projects. More successful DfMA application cases will encourage the diffusion of DfMA in the AEC industry.

3.5 Chapter summary

This chapter provides an overview of the definition, development, challenges, and integration of DfMA with BIM. By combining the literature from Chapters 2 and 3, this chapter identifies research gaps in digital-enabled DfMA and lays the theoretical foundation for the next chapter to carry out a relevant research design.

Chapter 4 Research Design and Methodology

4.1 Introduction

Following Saunders et al.'s (2009) research onion as a framework, this chapter presents the methodology applied to approach the research aims. It begins with the philosophical underpinnings of research and briefly summarises the key philosophical traditions and assumptions. This chapter then presents the research approach, design and process. In general, this research employs critical realism and interpretivism; through the use of abductive reasoning for a single case analysis.

4.2 Research philosophy

4.2.1 Ontological position – critical realism

4.2.1.1 Introduction of ontology

In philosophy, as the most fundamental branch of metaphysics, ontology is the science of what is, of the kinds and structures of objects (Novikov & Novikov, 2013). Ontology studies being or existence and seek the classification, relationship, and explanation of entities (i.e. product, process and people), which is to determine what entities and what types of entities exist (Žukauskas et al., 2018). Thus, ontology has strong implications for conceptions of reality and asks the question: what is the nature of what we know? Within this research, particularly relevant ontological questions may include:

- what is design?
- what is the identity of a design? And
- what are the various modes of being of design?

Design involves dynamic relationships and interactions between people and between people with artefacts over time in the creation of artefacts. Various people perform tasks span disciplines, companies, and locations, leading to an evolving network of interrelated activities (Wynn et al., 2005). Thus, the key elements of design are not only humans, objects and tasks but also the interactions between them, which is even more significant than the former. Therefore, understanding these interactions is needed to define and assess the design.

In terms of building systems integration, relevant ontological questions would also include:

- what is the building system?
- what is the identity of building systems? And
- what are the various modes of being of building systems?

Building systems are sets of interrelated and interconnected elements providing foundations for the designed performance of a building (Bachman, 2004). Thus, in essence, the research investigated the impact of evolving networks of interrelated humans, objects and tasks (i.e. design) on an evolving network of irrelated building elements (i.e. building systems). Understanding the impact between these two evolving networks is critical in this research for an emergent view of DfMA. As a routine engineered building product, it is likely to result in an overly mechanistic, systematised and hard outcome without considering interactions between two complex evolving networks. Creating excessively controlled DfMA processes using structured tools that do not acknowledge differences in stakeholder knowledge about design and elements of building systems can result in lost learning opportunities and a lack of flexibility. Besides, overly open and human-driven ‘designing by committee’ processes, centred on changing expectations and experiences, can limit the benefits of economies of scale and standardisation, leading to a loss of control (Mills, 2013). Thus, theory development must understand the nature of interactions between these two evolving networks.

4.2.1.2 Critical realism taken in this research

Critical realism is the stance taken as the ontological position in this research. Critical realists tend to accept that much of objective realities exist independently of our awareness or knowledge of them by reconciling the realist and relativist positions, similar to positivism (Easton, 2010). However, critical realists do not believe in positivist reasoning in understanding the world. In contrast, it is critical of the position that observations can necessarily provide knowledge of that reality (Easton, 2010). Similar to relativism, critical realists believe that cultures, history and society all influence individuals (Trochim & Donnelly, 2001). Individuals, including researchers, are always biased in their own truths, observations, and opinions.

Therefore, critical realism tries to adopt a layered ontology position with three domains to reconcile these two conflicting stances (Fairclough, 2005). Firstly, regarding the real domain, it may or may not observe the underlying and enduring causal structures and mechanisms of reality. Secondly, regarding the actual (observable) domain, it represents the visible manifestations of the real, which is the domain of events and processes, recordable by observation. Thirdly, regarding to the empirical (observed and understood) domain, it represents the part of the real and actual domains experienced and interpreted by social actors (Fairclough, 2005).

Critical realism in the ontological position has an impact on this research. Firstly, as the world exists independently of our knowledge of it, this research regards architectural design and building systems as entities independent from our knowledge. In addition, knowledge about BIM and DfMA is fallible and theory-laden. As the world is differentiated and stratified (Easton, 2010), the research believes there are underlying structures of DfMA. Furthermore, the underlying structure of digital-enabled DfMA has powers and liabilities capable of integrating building systems in healthcare construction. This underlying structure is also called the ‘real’ by Fairclough (2005).

Within the framework of 'stratified ontology' of critical realism, in this research, the 'actual', for example, includes the domain of DfMA events and processes, BIM events and processes, and building systems' events and processes. For the 'empirical', it is part of the real and the actual that is experienced by designers. In this research, the events and processes, such as integrating building systems, cannot reflect the 'real' in any simple or straightforward way. The extent to which and ways in which the particular causal powers are activated to affect actual events in contingent on the complex integration of different structures and causal powers in the causing of events. Causal powers between DfMA and building systems integration moreover are not exclusively the properties of underlying structures: stakeholders of healthcare construction projects also have causal powers affecting the actual. Thus, the causality cannot be consistent with the (Humean) 'constant conjunction' view (Archer et al., 2013).

4.2.2 Epistemological position – interpretivism

4.2.2.1 Introduction of epistemology

Closely entwined, epistemology and ontology occupy or should occupy the top of a hierarchy before shaping a specific research project. Invented in Western philosophy, post-Enlightenment (Williams, 2016), epistemology is the theory of scientific cognition (Novikov & Novikov, 2013) and is concerned with ensuring adequate and legitimate knowledge. As a branch of philosophy concerned with knowledge, epistemology is about how we, as humans, can know things, which represents *how we know what we know* (Crotty, 2020). Epistemology provides the logic of an enquiry and concerns the nature of knowledge, its possibility, scope and general basis (Hamlyn, 1995). Specifically, the nature of research questions and corresponding methodologies and methods is defined by our understanding of what knowledge is and how it is acquired.

Particularly relevant epistemological questions in this research may include:

- do we know a design? and if we do
- how do we know design and create knowledge of design?
- when do we know our knowledge of design as ‘true’ and how?
- how can the extent of the applicability of design knowledge be determined?

It is essential to understand the relationships between knowledge, truth, belief, reason, evidence, and reliability to answer the above-mentioned questions, which requires considering various epistemology routes to knowledge.

4.2.2.2 Epistemological position taken in this research: interpretivism

The research employed interpretivism epistemology. Interpretivism responds to the over-dominance of positivism (Saunders et al., 2009). The basic idea of interpretivism is that researchers form part of the research, and it emphasises specific, contextualized circumstances to view reality and knowledge as not objective but human-influenced (Alharahsheh & Pius, 2020). Meanings are emergent during the research process embodying researchers’ values inherently. Interpretivism relies heavily on naturalistic methods (interviewing, observation, and analysis of existing texts), which ensures dialogue between the researchers and those with whom they interact to construct a meaningful reality collaboratively (Hiller, 2016).

Interpretive researchers further concluded that there are essential epistemological differences between the natural sciences and the social sciences: using the perspectives of correlators and interpreters, respectively (Bishop, 2007). The correlators perspective focuses only on the physical-biological world and the dynamic causal structures that make it up, whereas the interpreter’s perspective explores the actors’ intentions, beliefs, emotions, opinions, and cultural-historical contexts (Bishop, 2007). Compared with the correlators’ perspective purely focusing on the explanatory relationship in the field of natural sciences, the existence of the abovementioned subjective concepts also makes the interpreter’s perspective more significant in the field of social science research. Further, Gadamer (2008) argues that the purpose of researchers is not just to understand the thoughts and intentions of research objects but to clarify and reveal truthful thoughts through understanding research objects. Understanding in research involves the interaction between the parts of the whole and is a process constantly being created as times and circumstances change (Saunders et al., 2009). Interpretation, therefore, relies on the overall thinking of the researcher. The approach to combining critical realism on ontology and interpretivism on epistemology is illustrated in the following sections for how they represent and influence the case study design.

4.3 Reasoning approach

The research approach is to address the research aim and objectives. There are three primary reasoning methods: deductive, inductive, and abductive (Creswell, 2009; Niiniluoto, 1999). The reasoning is the process of using existing knowledge to conclude, make predictions, or construct explanations. Either independently or concurrently, adopting these three reasoning approaches impacts the development of the research design (Easterby-Smith et al., 2012) and research strategies (Fellows & Liu, 2021). Inductive and deductive reasoning are the two most common research reasoning approaches and have a rigid division between them (Saunders et al., 2009). An integrated combination of inductive and deductive reasoning somehow provides increased advantages (Miles & Huberman, 1994) which might promote a more profound ‘theory-forming or interpretive inference’ for understanding data than these two reasonings (Saunders et al., 2009).

Abductive reasoning, also referred to as the abductive approach, beginning in the last third of the 19th century, combines inductive and deductive reasoning into an iterative, pragmatic and dynamic approach (Creswell & Poth, 2016). Starting with real-life and usually an incomplete set of observations, deductive reasoning then seeks the pattern explanation, theme discovery, phenomena examination, and finally, theory creation. Integrating by moving back and forth between inductive and deductive methods, abductive reasoning builds deep theoretical insights in this way (Paul, 1993). Therefore, this research adopted a mixed-method research design with abductive reasoning to understand digital-enabled DfMA in healthcare construction. Modularity theory as a theoretical lens was used in this process to investigate building systems integration, which then laid the foundation for integrated approaches to digital-enabled DfMA.

There are two research stages in this research (see Figure 10). At the preliminary stage, a deductive approach was adopted to explore the perceptual measures of BIM and DfMA in healthcare construction to understand their current status. As a 'top-down' approach, deductive reasoning uses a general idea to establish a specific conclusion to explain or understand an event or phenomenon (Graneheim et al., 2017). From a theory, deductive reasoning then derives and tests the hypothesis and revises the theory (Woiceshyn & Daellenbach, 2018). In this research, deductive reasoning started with developing an understanding to the application of digital-enabled approaches and DfMA within China's healthcare construction industry. The understanding provides a general idea of how digital-enabled design facilitates building systems integration of healthcare construction. Analysing BIM and DfMA in China's healthcare construction confirms or rejects the established literature or theory, allowing for an in-depth understanding of digital-enabled DfMA to emerge and a revision of the literature or theory to take place.

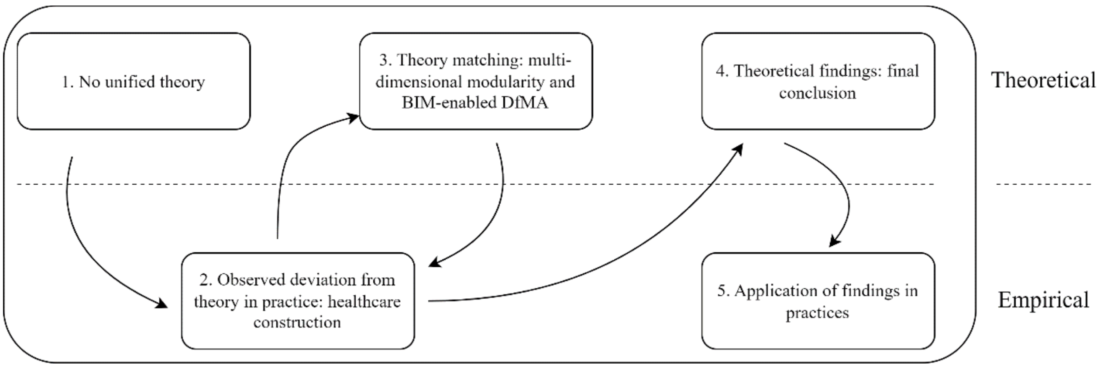


Figure 10 Abductive reasoning in this research

In the primary research phase, the research then turned to the use of induction approaches to explore: 1) how are digital-enabled approaches (i.e. BIM) and DfMA implemented, and what are the underlying modularity principles of the implementation? 2) how to effectively facilitate the implementation of digital-enabled DfMA through modularity principles? Induction is more suitable for answering 'why' and 'how' questions than for describing 'what' questions. As a 'bottom-up' approach informally, inductive reasoning moves from specific observation to broader generalisations and theories (Fellows & Liu, 2021) and entails using existing knowledge or observations to make predictions about novel cases (Hayes et al., 2010). The inductive conclusion is more than a restatement of the premises and is sometimes dubbed an ampliative form of reasoning (Salmon, 2017). In China, the challenges of building systems integration in the field of healthcare construction are still significant, and digital technologies, OSC practices, and new design concepts, such as DfMA, have not been carried out very effectively, which causes a spiral (constantly going back and forth) flow to move from deductive to inductive mode. Identifying a novel and unique case for inductive reasoning could broaden the existing understanding of digital-enabled DfMA.

Due to its ability for the best interpretation, abductive reasoning facilitates further in-depth capture and understanding of digital-enabled DfMA both empirically and theoretically. Whether it is BIM, modularity, or DfMA, there are still some very emerging fields in the healthcare construction practice in China, so using abductive reasoning can be a good way to gain insights into this new situation. In addition, abductive reasoning, as a combination of inductive and deductive methods, can help creatively push the limits, obtaining and compiling more data to lay the foundation for a final theory formulation. This provided a clearer framework for understanding the relationship between multiple dimensions of modularity in the novel situation, which subsequently developed a further understanding of DfMA and achieved the research aim.

4.4 Research methodology

4.4.1 Understand the context of healthcare construction

In step 1, this research adopted a survey to understand the basic situation regarding digital and DfMA practices in China's healthcare construction. This survey involves an online questionnaire survey and a series of semi-structured interviews. The descriptive survey research explores, describes and understands current DfMA and digital practices in China's healthcare construction. There are four objectives:1) to explore DfMA practices in healthcare construction, 2) to explore digital-enabled approaches in healthcare construction; 3) to explore adoption factors of DfMA and digital-enabled approaches (i.e. BIM), 4) to investigate attitudes and recommendations for the industry to increase the take-up of DfMA or digital-enabled approaches in healthcare construction.

By basing on responses' reveal of real-life experience, the descriptive survey research aims to establish a preliminary understanding of current and emerging design practices, challenges, and trends in China's healthcare construction. The descriptive survey research contributed to the answer to research question 1, and it played a foundation role in the following interview-based research in the preliminary stage and the case study in the main study component. The survey involves the type of quantitative research that uses the form of descriptive design and the type of qualitative research that uses the form of interview-based research. For the characteristics of the early stage of research projects, descriptive research can generate unique research value by describing the phenomenon (Glatthorn & Joyner, 2005). This type of research does not draw conclusions about the relationship between the subjects under investigation (Glatthorn & Joyner, 2005). Instead, descriptive research focuses on outcomes, averages and percentages, e.g., identifying attitudes. Questionnaire surveys make it faster and easier to obtain a large amount of data in the initial stage and provide convenience for the respondents (Fowler Jr, 2013). Nevertheless, its disadvantage is that there is no direct communication between researchers and respondents, which hinders in-depth data collection (Fowler Jr, 2013). Interviews were therefore used as an essential data supplement.

The interview-based part aims to enrich the results generated from the questionnaire and explore the identified questions within the project context. The main data collection of the survey was completed during the period from April 2021 to January 2022. Interview research is ‘conducting intensive individual interviews with a small number of respondents to explore their perspectives on a particular idea, program or situation’ (Boyce & Neale, 2006). There are three fundamental types of interviews in research: structured, semi-structured, and unstructured (Gillham, 2001). Semi-structured interviews eliminate the disadvantages of either highly flexible or highly fixed from unstructured and structured interviews, and it gives the authority of management and sequences the proposed questions to the interviewer (Schmidt, 2004). As the most commonly used qualitative research method, the semi-structured interview provides sufficient flexibility to approach different informants covering a similar area of data collection (Noor, 2008). Standing on a romanticism view of interview research, the semi-structured interview is used to explore and understand the interviewees’ inner world through a human encounter between interviewers and interviewees (Schmidt, 2004).

There are two objectives:1) to understand the current practice of digital-enabled approaches (i.e. BIM) in healthcare construction. 2) to explore DfMA in the healthcare building process. By basing on the interviewees’ reveal of real-life experiences and various complex social realities, the interview research aims to enrich and further the survey research by establishing an in-depth understanding of current and emerging design practices, challenges, and trends in China’s healthcare construction. The semi-structured interview contributed to the answer to research questions 1 and 2, and it played a foundation role in the following main study component.

4.4.2 Case under China’s COVID-19

4.4.2.1 Identification of case study

There is no universal formula to address the use of the case study method (Groat & Wang, 2013). In essence, the case study research is more relevant to dealing with explaining present circumstances (e.g., ‘how’ or ‘why’ some social phenomenon works), and especially for the requirements of extensive and in-depth descriptions of some social phenomenon. There is no easy explanation for the case study (Gustafsson, 2017).

Yin (2017) defines twofold definitions covering the scope and features. For the scope of a case study (Gustafsson, 2017). Yin (2017) defines a case study as an empirical inquiry that ‘*investigates a contemporary phenomenon (the ‘case’) in depth and within its real-world context, especially when the boundaries between phenomenon and context may not be clearly evident.*’ In addition, due to the situation of not always sharply distinguishable between phenomenon and context, Yin (2017) further defines a case study inquiry: ‘*1) Copes with the technically distinctive situation in which there will be many more variables of interest then data points, and as one result; 2) Relies on multiple sources of evidence, with data needing to converge in a triangulating fashion, and as another result; and 3) Benefits from the prior development of theoretical propositions to guide data collection and analysis.’*

Groat and Wang (2013) amend Yin’s (2017) definition of case study to be more applicable to architectural research by deleting the word contemporary and adding the word setting: *an empirical inquiry that investigates a phenomenon or setting.* Groat and Wang (2013) further summarise five characteristics of case studies in architectural research, including 1) a focus on either single or multiple cases, studied in their real-life contexts; 2) the capacity to explain causal links; 3) the importance of theory development in the research design phase; 4) a reliance on multiple sources of evidence, with data converging in a triangular fashion; and 5) the power to generalise to theory.

This research adopts the case study research for its capabilities in replying to the research question: ‘How has DfMA been implemented in healthcare construction, and how has the traditional design process been modified or changed to support healthcare building systems integration?’ There are three general reasons to justify the choice. Firstly, ‘how’ questions are more explanatory and involve operational links that need to be tracked over time, not just frequency or incidence (Yin, 2017). This type of question can lead to a case study method which is also good at dealing with 'how' questions. In this research, the transformation of the design process and implementation of DfMA are a series of continuous actions over time. And these DfMA actions are embedded into the whole AEC industry and project contexts and cannot be separated from real-life contexts.

Secondly, the case study can use multiple sources for theoretical generalisation (Yin, 2017). This research aims to generate knowledge and theories in DfMA by using a modularity lens. As the focus on building systems integration, the research emphasised multidisciplinary collaboration in design and construction, which requires multiple data sources for evidence and justification. The case study provides a solid approach to the synergy of multiple data sources from various design disciplines to understand DfMA and building systems integration. Thirdly, the AEC industry is a typical project-based industry. There are clear boundaries between one architectural project and the other, including the people, the organisation, and the design and construction. The project is, therefore, ideal for case study research. This research regards a healthcare project as a single case and a special unit for analysis.

4.4.2.2 Identification of single case study

The case study can be either single or multiple (see Figure 11). There is no one-for-all formula to decide the number of cases necessary for a multiple-case design, such as the choice between single- and multiple-case designs (Groat & Wang, 2013). Groat and Wang (2013) propose two principles for the decision-making of the case study strategy: 1) the nature of the theoretical questions, or research questions, involved; and 2) the role of replication in testing or confirming the research's outcomes. Thus, this research chose a single case study to explore the research question. In the architecture field, many established examples of single exist. For example, Jacobs (1961) uses New York City as a particular single case to explore the multiple socio-physical dynamics that contribute to the vitality of urban life. A single case study can be highly compelling and – as with Jacobs's study – very influential (Groat & Wang, 2013).

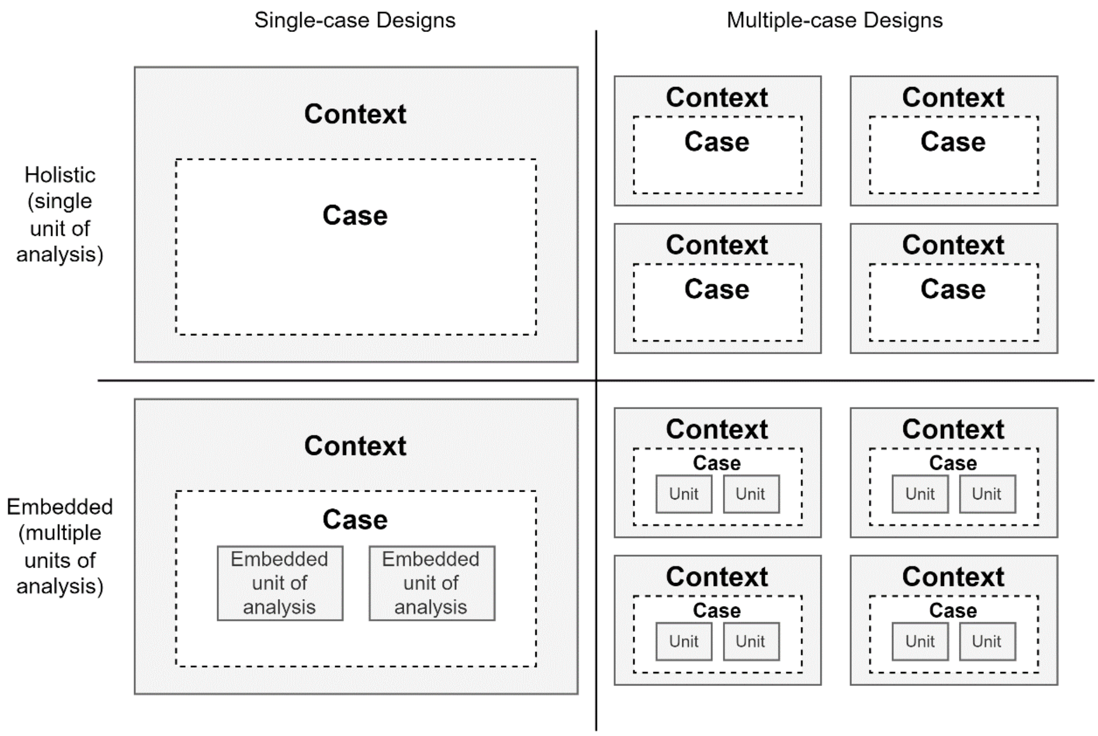


Figure 11 Basic types of case study design (Yin, 2017)

Yin (2017) argues five rationales for single-case designs: having a critical, unusual, common, revelatory, or longitudinal case (see Table 5). This research adopted Yin's (2017) classification to justify the use of the case study. To answer the research question: How has DfMA been implemented in healthcare construction, and how has the traditional design process been modified or changed to support healthcare building systems integration, three rationales from these five rationales were identified for the choice of single case study, namely 1) critical case; 2) extreme/unique case; and 3) revelatory case.

(See Table 5 on the next page)

Table 5 Types of case studies (Thomas, 2011)

George and Bennett (2005)	**De Vaus (2001)**	**Mitchell (2006)**	**Yin (2017)**
Theory testing	Descriptive/explanatory	Illustrative	Critical
Atheoretical/configurative-idiographic	Theory testing/theory building	Social analytic	Extreme/unique
Disciplined configurative	Single/multiple case	Extended (over time)	Longitudinal
Heuristic	Holistic/embedded	Configurative-idiographic	Representative
Plausibility probes	Parallel/sequential	Disciplined-configurative	Revelatory
'Building block' studies	Retrospective/prospective	Heuristic	
		Plausibility probes	

Firstly, selecting a single case can be justified when it is critical to the theory or theoretical propositions (Yin, 2017). A single case was selected in this research to test the modularity theory. The propositions from modularity theory can be explored through a single case for its correction or whether some alternative set of explanations might be more relevant.

Secondly, by revealing insights about normal processes, selecting a single case can be justified for its characteristics of extreme/unique deviating from theoretical norms or even everyday occurrences (Yin, 2017). DfMA and modularity theory were first developed in other industries and then introduced into the AEC industry. Using extreme/unique cases would benefit from connecting the theories to many cases in the AEC industry.

Thirdly, bringing to light the revelatory nature through exposure to previously inaccessible phenomena can also be used to justify the selection of a single case study in theory building (Yin, 2017). In this research, the descriptive information of both BIM and DfMA in healthcare construction is revelatory. Due to COVID-19, there was an inaccessible phenomenon of rapid emergency healthcare construction around the world, providing an opportunity to bring to light the revelatory nature.

Finally, regarding the criticism for generation, the single case study is not for the representation of the world but for the representation of the case (Stake, 1978), which means the main goal is to pursue a better view and explanation rather than seek the general laws that operate in the particular case (Tsoukas, 2009).

4.4.2.3 Identification of case study paradigm

The ontological and epistemological stance of this research influences the methodology of the case study. The ontological stance of critical realism assumes the existence of a multi-layered objective reality in society and culture. This position attempts to articulate it in terms of a 'good' scientific method, assuming that such methodological skills describe the reality of the subject and advance scientific knowledge. The core of interpretivist epistemology is 'understanding' (Alharahsheh & Pius, 2020). Case studies sharing understandings may be beyond normal understanding and imagination (Yin, 2017). The value of a case study under epistemological interpretivism lies in explaining how a case under investigation takes place. Such an explanation must be meaningful in the context of real-life situations.

Based on the epistemology of interpretivism, the research design needs to articulate a well-defined research question (with the 'How' as the frame, which aims to present concepts and their interrelationships); second, the research needs to do an initial exploration of the existing literature, but not judge its conclusions yet. A case study under epistemological interpretivism emphasises in-depth, long-term research and observation, and emphasises the effective use of non-interview data (e.g., documents, letters, annual reports, seminars, archives).

For data collection, it prefers theoretical sampling. And the principle of combining primary interview and observation data with secondary archival data is often adopted. Data analysis and induction process are from first-order and second-order coding to overall theoretical dimensions and theoretical models. In terms of interpretivism-oriented writing, a study is usually developed in chronological order for a complex case, and the description of the situation is also the focus of case narrative and analysis. Concepts such as ‘process’, ‘structure’, ‘emergence’, ‘pattern’, ‘insight’, ‘understanding’, ‘interpretation’ and ‘experience’ appeared more frequently in the research and writing process.

4.5 Research case selection

This research sampling aims to achieve theoretical generalisability through a critical, extreme and revelatory case. Therefore, the selection of the healthcare design case should shed empirical light on theoretical concepts or principles of modularity. In addition, this case should develop intensive, ‘thick descriptions’ of the process of DfMA at one hospital project (Harrison et al., 2017). Embedded within this are multiple accounts of DfMA implementation in various design disciplines.

Many studies have studied and highlighted the emergency hospital in Wuhan for COVID-19 (Chen et al., 2021; Luo et al., 2020; Wang et al., 2021). Huoshenshan Hospital provides an example of a rapidly deployed healthcare facility to increase capacity to cope with increased hospitalisations of COVID-19 patients in Wuhan, China. This project is the first emergency hospital built worldwide since the outbreak of COVID-19 and is well-known for its rapid design and construction. It is a unique opportunity to explore DfMA due to the high uncertainty, limited time, complex functionality and rapid capability of the hospital design. There were more than 100 stakeholders in the project. On January 23, 2020, the Wuhan Government decided to build Huoshenshan Hospital with 33,940 square meters and 1,000 beds. After ten days, Wuhan Huoshenshan Hospital was completed on February 2, 2020.

General Institute of Architectural Design and Research Co., Ltd. (CITIC) and China Construction Third Engineering Bureau Co., Ltd. were involved as the main actors in the design and construction. They worked closely with local sub-contractors, government departments and suppliers to coordinate and integrate building systems. The CITIC's team acted as a design unit responsible for negotiating and making design and technological decisions with limited time and available resources. Similarly, the Chinese government last time had combated the severe acute respiratory syndrome outbreak through a modular healthcare project in Beijing, namely Xiaotangshan Hospital, in 2003. Designers saw in the Huoshenshan an opportunity to rapidly industrialise their design results for a modular hospital. For CITIC, Huoshenshan meant consolidating all its design disciplines in a single complex building system. The project used DfMA for its rapid construction. All participants devoted themselves to completing the design and construction quicker than the proposed target time, even during the Chinese Spring Festival. The first ward building was completed in only 16 hours and rapidly handed over for beneficial occupation.

To understand the role and capabilities of DfMA for the rapid delivery of systems integrated healthcare projects, this research conducted an inductive, interpretive, qualitative enquiry (Eisenhardt et al., 2016; Gioia et al., 2013) through a single case study for its superiority of critically questioning, verifying and extending old theoretical relationships (Eisenhardt & Graebner, 2007; Flyvbjerg, 2006; Yin, 2017). This research approach allowed a specific and contextual implementation of DfMA, which promoted an understanding of the principles and philosophies beyond guidelines.

4.6 Data collection

4.6.1 Research step 1: Questionnaire survey

This research developed a survey instrument through a literature review, information interviews, discussion with leading researchers and industrial contact from healthcare construction. Documents and literature from China's leading organisations and governments were mainly used to design the survey to better fit the language and education of local practitioners. For example, the research referred to measures, characteristics and benefits published by the Chinese government regarding BIM and OSC to design the survey questionnaire and answering options. The major document is the "Several Opinions on Accelerating the Development of New Building Industrialization" from the Ministry of Housing and Urban-Rural Development. A pilot survey with a few research colleagues was conducted to verify the validity and reliability of the survey. Finally, a package of questionnaire survey instrument was established. Both qualitative and quantitative questions are included within the instrument with a methodical use of rating scales, Likert scales and open-ended questions. Section 1 aims to establish an overview of the sampling, including their company types, professionals, and work years. Section 2 explores the industrialised practices in healthcare construction. Section 3 explores digital-enabled approaches in healthcare construction. Section 4 and section 5 search for the adoption factors of industrialised technologies and BIM respectively. And section 6 investigates attitudes and recommendations for the industry to increase the take-up of industrialised or digitalised practices in healthcare construction.

The instrument has clear instructions and an easy-reading layout for increasing response rate. Tencent Questionnaire, an online platform, was used to develop the survey, distribute the questionnaire and collect data. The distribution involved two major routes, namely distribution through the WeChat group of healthcare construction and distribution through the 'answer group', which is a function to distribute questionnaire surveys to specific WeChat users directly and individually. This distribution is designed for practitioners with healthcare construction experience. The distribution of questionnaires through WeChat is limited as it may not reach audiences who do not use WeChat, and the responses may be influenced by biases in the social media environment. This study mitigated the limitations of using WeChat for questionnaire distribution by supplementing it with alternative data collection methods like interviews and document analysis, thus ensuring a more comprehensive understanding of the single case's context. The data collection of the survey was completed in October 2021.

4.6.2 Research step 2: Supplementary interviews to the survey

Healthcare construction involves multi-disciplinary collaboration between various design professionals. The sampling involving various disciplines can help understand DfMA from multiple aspects, which contributes to exploring the integration of DfMA strategies. Various engineering design backgrounds can include architectural design, structural engineering, water supply engineering, HVAC engineering, Electrical engineering, and power engineering. Both senior designers, such as leaders and principals, and junior designers were included for a better understanding of various levels of design. The inclusion criteria include: 1) project experience from China; 2) having experience in healthcare design; 3) having experience in prefabricated healthcare design; 4) working for leading design institutions or projects. The organisations or projects awarded national or industry-level awards can be recognised as leading practitioners in this context. These proposed criteria would contribute to identifying cutting-edge situations and challenges faced by China's industry of healthcare construction.

The recruitment strategy follows a top-down approach, which is suitable for the situation of China. As some middle or junior level designers cannot decide whether it is appropriate to expose their previous projects' experience, the research first approached the architect leader of the protentional company for research collaboration. Based on the architect leader's arrangement, other middle or junior-level designers from various disciplines can be easily approached. Phone calls or online calls through WeChat were the two primary modes of contacting potential interviewees and scheduling interviews. All required documents were received through WeChat. Chinese was used as the major language for the interview. As shown in Table 6, the sample of interviewees includes 13 designers from six disciplines.

(See Table 6 on the next page)

Table 6 Sample of interviewees

Code	Specialization	Role	Working years	Years in healthcare construction
P01	Architectural design	Leader	22	22
P02		Leader	13	7
P03		Designer	4	4
P04		Designer	1.5	1.5
P05	Structural engineering	Leader	9	9
P06		Designer	3	3
P07	Water supply and drainage	Leader	N/A	N/A
P08		Designer	3	3
P09	HVAC	Leader	N/A	N/A
P10		Leader	5	5
P11		Designer	12	5
P12	Electrical engineering	Leader	17	5
P13	Power engineering	Leader	15	15

All interviewees were informed of 1) the research, such as objectives, methods, and data use; 2) the researcher, such as affiliation, participants, and contact details; 3) the data protection, such as anonymization. Relevant documents, such as the research information sheet (see Appendix 2) and research consent form (see Appendix 3), were sent to interviewers for signature. After the collection of signatures, the interviews were conducted. The theoretical foundation of modularity and DfMA were utilised as the interview guideline.

There are four major categories of information required in the research: 1) general information of an interviewee; 2) general information on healthcare construction; 3) design strategies for healthcare construction; and 4) adoption of industrialised and digitalised techniques (see Table 7). Following these four categories' interview, the additional five (see 'other' in Table 7) would let interviewees to sharing what they think might be significant for healthcare design and provide them opportunities to ask questions towards the interviewer, which provide an opportunity for the interaction between the interviewer and interviewees for more in-depth discussion. The questions asked are based on the information required above. During the interview, based on the interviewees' answers, relevant emerging questions were asked for supplements. The interview time ranged from 30-90 minutes. All interviews were recorded, translated, and transcribed.

(See Table 7 on the next page)

Table 7 Areas of information required in the interviews

Areas of information required	Information required
General information of an interviewee	Roles of interviewees
	Working years (both in the general AEC industry and healthcare construction)
	Responsibilities in previous healthcare construction projects
General information on healthcare construction	Differences between healthcare construction and other sectors
	Difficulties in healthcare construction
	Requirements of healthcare construction
Design strategies for healthcare construction	Participants and stakeholders for healthcare design
	Integration and collaboration between design and construction
	Design evaluation method
	Decision-making in design
	Integration of design guidelines/strategies
Adoption of industrialised and digitalised techniques	Approaches/techniques for the improvement of manufacturability and assemblability
	Digital approaches/techniques to facilitate design
Other	Significant experience from previous projects can be used for following projects
	Significant experience and suggestions for sharing

4.6.3 Research step 3: Huoshenshan Hospital

Based on the epistemology of interpretivism, the data collection of the case study paradigm should focus on: (1) giving more opportunities to those who have deep insights into the problem; (2) maintaining flexibility and adjusting the interview outline according to the respondents' answers; (3) re-investigate the previous interviewees according to the problems encountered in the later interviews. This research adopted semi-structured interviews for their advantages in combining both the structured and unstructured interview styles and offering opportunities to explore specific topics spontaneously (Galletta, 2013). The semi-structured interview is almost equated with the main method of collecting qualitative data for case research because of its flexibility (Easton, 2010). This research approach avails an opportunity to interpret the meaning of experience as lived by participants to gain fresh perspectives (Creswell, 2007).

The research employed two inclusion criteria for participant selection: 1) active involvement in the design process of Huoshenshan Hospital project, and 2) designation as a designer. The concept of saturation, according to Saunders et al. (2018), should align with the research questions, theoretical position, and analytical framework employed. This study aims to achieve theoretical saturation to bolster the validity and reliability of the findings, given the research philosophy and questions. As described by Hennink et al. (2017), theoretical saturation is attained when data collection ceases to reveal additional insights and all pertinent conceptual categories have been thoroughly examined. Specifically, this study endeavours to reach theoretical saturation within the sample to exhaustively identify the reinforcement relationships among integrated approaches pertinent to the primary research question.

The Huoshenshan Hospital project had a designer population of approximately 60 participants from the CITIC, comprising five design specialisations: architectural design, structural engineering, water supply and drainage, HVAC, and electrical engineering. The aim of this research was to attain theoretical saturation by interviewing all five design specialisations regarding their practices of BIM and DfMA. The junior designers reported their progress to their respective leaders who managed the primary flow of information for their specializations. As such, this research aimed to interview both senior design leaders and junior designers.

The purposive sampling strategy combined critical case sampling and stratified sampling to specify categories of persons to be included in the sample. Hereafter, a written invitation coupled with a schematic presentation of questions (shown in Table 8), explaining the purpose of the semi-structured interview, was sent to the participants before telephone interviews. The authors contacted 90% of Huoshenshan Hospital designer population members, and the junior designers not engaged throughout the design were not contacted. Table 9 shows the 18 interviews undertaken. All interviews lasted between 30 and 60 min and were recorded with the permission of the interviewees. The data collection satisfied theoretical saturation through the following ways: 1) continuously analyse data and compare it to emerging themes until the stop of emerging and becoming redundant; 2) look for disconfirming evidence to test and refine emerging themes; 3) Seek feedback from peers and subject matter experts to ensure the reliability of findings.

Table 8 Interview questions

No.	Questions
1	Could you describe the project, including your role and responsibilities?
2	Could you describe the required outcomes, especially about manufacturability and assemblability?
3	Could you describe the strategies to improve DfMA. How were these strategies integrated?
4	Who was involved in the design stage? What should design and construction team integration look like? Were there any specific digital techniques that made it possible (e.g. BIM)?
5	Could you describe the design evaluation approaches used in this project?
6	Could you describe the decision-making process of design? Who was involved in the decision-making?
7	Could you describe challenges to DfMA? Were there any digital advancements to the application of DFMA?
8	Are there any lessons that you would take on to the next project?
9	Are there any important experience or opinions about the project that you want to add?

(See Table 9 on the next page)

Table 9 Sample of interviewees

Code	Specialisation	Role	Working years
C1	Architectural design	Leader	> 16
C2		Designing principal	> 16
C3		On-site designer	11-15
C4		Designer	6-10
C5	Structural engineering	Leader	> 16
C6			> 16
C7		Designing principal	> 16
C8	Water supply and drainage	Leader	> 16
C9		Designing principal	> 16
C10		Designer	11-15
C11			11-15
C12			6-10
C13	HVAC	Leader	> 16
C14		Designing principal	> 16
C15		Designer	11-15
C16	Electrical engineering	Leader	> 16
C17		Designing principal	> 16
C18		Designer	> 16

As shown in Figure 12, semi-structured interviews were combined with multiple other data sources, including one focus group, public news, reports, and interviews, and published books and documents. This mixed-method supported data validation and triangulation. In the first period, various resources were reviewed to understand the basic information about the project case and the design institute. China National Knowledge Infrastructure (CNKI) was used to download all Huoshenshan-related Chinese reports, news and technical analyses. These documents provided essential knowledge and understanding about the project. Two authors then organised a focus group discussion with the CITIC for their traditional practices about BIM and DfMA, which provided a context to understand the uniqueness of Huoshenshan

Hospital. Five directors, one researcher from the CITIC, and one associate professor in construction management from the local university joined the focus group discussion. In the last period, newly uploaded documents about Huoshenshan were reviewed from CNKI, and an official book about the detailed technical information of Huoshenshan was used to validate the interviews. The research content was finally checked and discussed with the designers to form the triangulated validation.

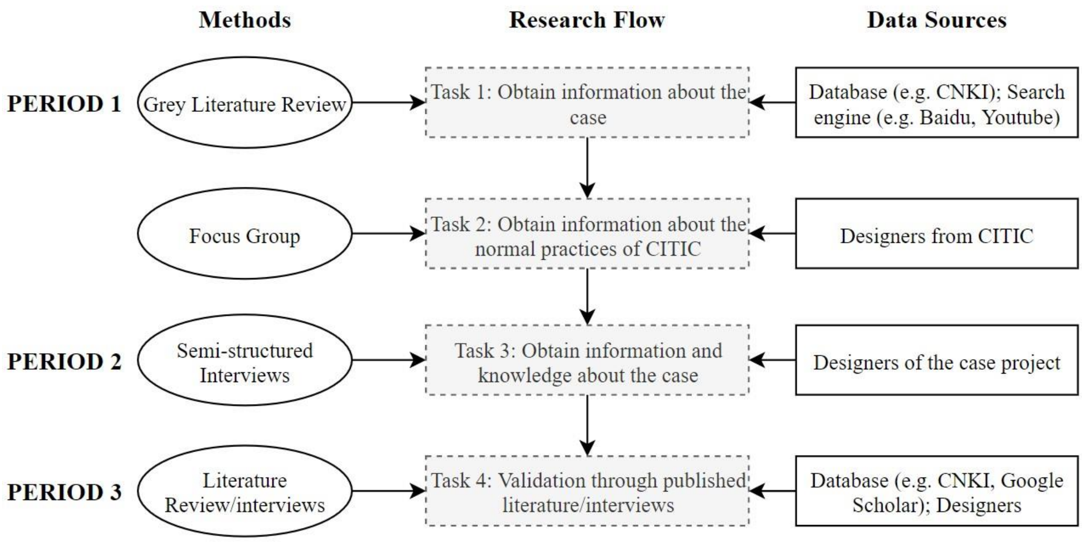


Figure 12 Research methods for the single case of Huoshenshan Hospital

4.7 Data analysis

4.7.1 Quantitative data analysis: descriptive statistics for survey

Descriptive research is suitable for describing the characteristics of a population or phenomenon in order to solve the 'what' question rather than answer questions related to how/when/why the characteristics occurred (Shields & Rangarajan, 2013). This type of research aims to understand respondents' attitudes and opinions about phenomena, thereby helping to draw patterns, traits, and behaviours by using frequencies, averages and other statistical calculations (Thomlison, 2001). Conducting a survey investigation is the best approach prior to writing descriptive research. This approach is beneficial for collecting a large amount of data in a limited time for pattern recognition, which can contain open-ended and closed-ended problems to obtain vast data from heterogeneous responders.

For survey analysis, both Microsoft Excel and Tencent Questionnaire were used for storing data. And the latter was used to analyse, illustrate and present the data. Descriptive statistics are used to describe a summary of the basic characteristics of the sample and observations made in a study (Fisher & Marshall, 2009). Both quantitative summary statistics and visual simple-to-understand graphs are used to form simple summaries about samples and measures, which form the basis for a preliminary description of the data as part of a broader statistical analysis. In addition, they may also be in and of themselves for a particular investigation (Trochim, 2006). Univariate analysis is a major data analysis method in this part of the research (Ho, 2006), focuses on analysing one variable at a time to understand its distribution, central tendency, and spread. It helps in identifying trends, detecting outliers, and summarizing the characteristics of the data (Huberty & Morris, 1992).

4.7.2 Qualitative data analysis: thematic content analysis for interviews and the case study

4.7.2.1 Interview data analysis procedures

This interview research adopted qualitative content analysis which refers to systematically describing the meaning of qualitative data in an essentially descriptive way (Schreier, 2012). Rather than establish generalisations from data collection, the content analysis aims for the understanding of phenomenon by focusing on the subject and context (Forman & Damschroder, 2007). The analysis emphasises on variations, such as similarities and differences between parts of the data (Bazeley, 2013). This research adopted the three-step framework proposed by Forman and Damschroder (2007) to approach qualitative content analysis, including 1) data immersion; 2) data reduction; and 3) data interpretation.

Data immersion is about how researchers engage and obtain a sense of the data (Forman & Damschroder, 2007). A challenge in qualitative content analysis is that the data collection and analysis occur concurrently while there is no clear way to manage and analyse large amounts of data (Forman & Damschroder, 2007). Thus, engaging with the data early for coding development would contribute to effective analysis. During and after the interviews, the ‘comment sheet’ referring to an approach to record first impressions was used immediately, which contributed to future data collection, comparisons to data collected before and analytic hunches. Besides, ‘memoing’ is another essential way for the immersion stage. By writing down early throughs and hunches, memos serve as an approach to facilitate engagement and initiate the data analysis. In addition, listening and reading the audio recordings and transcripts were conducted several times (Forman & Damschroder, 2007).

Data reduction aims to : (1) reduce the amount of raw data to the amount relevant to answering the research question; (2) break down the data (including transcripts and memos) into more manageable themes and thematic segments; (3)) reorganise the data into categories in a way that addresses the research questions (Forman & Damschroder, 2007). At this stage, coding provides a systematic way to manage, locate, identify, and sort data (Bazeley, 2013). Codes are a classification system. As categories or themes (Graneheim et al., 2017), data could be coded to represent topics, concepts, or categories of events, processes, or beliefs. This research combined deductive and inductive codes, which means using the former as a way to ‘get into’ the data and the latter as a way to identify new codes and refine or even eliminate a priori codes (Forman & Damschroder, 2007).

Data interpretation refers to the process of reviewing data by adopting predetermined processes for assigning some meaning to the data and then arriving at a relevant conclusion (Forman & Damschroder, 2007). There is no clear boundary between data analysis and data interpretation (Forman & Damschroder, 2007). This step requires advancing analysis, making inferences on the relations studied and synthesis to generate conclusions. Although there are many ways of interpreting, the common denominator is that they all involve reorganizing data, writing descriptive and explanatory summaries, presenting key results, and drawing and validating conclusions (Miles & Huberman, 1994).

4.7.2.2 Case study analysis procedures

In the definition of research questions, interpretivism emphasises the understanding of the nature or meaning of the research phenomenon, which is reflected in the transformation process of people's cognition from the surface to the deep structure (Alharahsheh & Pius, 2020). Here, the deep structure is the cognitive framework that people follow in making fundamental, interdependent behavioural choices, embodied in the second-level coding (Gersick, 1991). Characteristics of data analysis under interpretivism case study include: (1) implementing initial data coding, maintaining the integrity of first-order (information-centric) terminology; (2) producing overall summary tables including first-order encoded entries; (3) organising first-order coding into second-order coding (theory-centric) topics; (4) generalising second-order coding topics into overall theoretical dimensions (if applicable); (5) combining items, topics, and dimensions into data structures middle.

Characteristics of data presentation under interpretivism case study include: (1) forming dynamic relationships between secondary concepts in data structures; (2) converting static data structures into dynamic grounded theoretical models; (3) literature dialogue, refining the representation of emerging concepts and their relationships. Interpretive case studies reflect the process of theoretical induction by emphasizing the encoding process of concepts. Specifically, researchers systematically presented first-order coding (analysed using respondent-centred terms and items) and second-order coding (analysed using researcher-centred concepts, themes, and dimensions, specifically looking out for concepts not present in the literature) to provide a basis for the concepts and theories that eventually emerge.

Content-driven thematic analysis was used to obtain meaning from the interview data (Morse, 1994) using Atlas-ti 9 qualitative data analysis tool. The analytical technique follows a general phenomenological approach where data was evaluated to identify significant statements and sentences that provide an understanding of how participants experienced the phenomenon (Creswell & Poth, 2016). This analytical technique is also known as horizontalisation (Leech

& Onwuegbuzie, 2008; Moustakas, 1994), which is followed by the careful development of clusters of meaning. Others have applied such methods to identify design and innovation strategies (Ajayi et al., 2017; Tang, 2020). The method has six phases: 1) familiarising with data; 2) generating initial codes; 3) searching for themes; 4) reviewing themes; 5) defining and naming themes; and 6) producing the report (Braun & Clarke, 2006).

In line with the procedure for thematic analysis, the coding scheme and final categorisation of identified factors were based on dominant themes that emerged from the interview scripts. The data-driven (inductive) coding process was adopted and manually implemented (Saldaña, 2021). The coding scheme enhanced the identification of key design attributes, strategies, as well as broad categories of measures for integrating DfMA. Atlas-ti 9 was used to facilitate initial data familiarisation to carry out a data-driven thematic analysis. Data coding was done using three categories of labelling (see Table 10). In addition to the identified comment from transcribed data, the three elements are code/super codes, discussion and measures. Based on initial word crunching, codes were used to search through each of the 18 transcripts of semi-structured interviews. The discussion represents the semi-structured interviews from which a comment was made, while measures are the summed-up statements and strategies derived from each comment. Table 10 demonstrates how the strategies were derived from thematic analysis.

(See Table 10 on the next page)

Table 10 Examples of coding data segments

Code/super codes	Interviews	Comments (from the data, highlighted by the code)	Measures (established from the comment)
Standardisation	S1	'I designed a standardised ward that can be replicated everywhere. In the future, when we encounter a similar emergency project, these reserved wards can be used immediately for this assembly-type project.'	Use standard modules
Collaboration	S2	'Four parties, including The CITIC, the healthcare operator, the main contractor and the government, participated in the decision-making and collaborated closely for the whole process.'	Collaborative decision-making to avoid changes
Integration	S3	'Designers from the main contractor worked in the CITIC for better communication. Each design discipline from CITIC allocated 1-2 designers to work on-site with the contractor.'	All disciplines have designers from the main contractor

4.8 Chapter summary

This chapter introduces the definitions, identifications and procedures of the critical realism position of ontology, interpretivism position of epistemology, abductive reasoning approach and single case study method adopted in this research, including data collection and data analysis methods. In the next chapter, the research presents the results of the status-quo of China's healthcare construction.

Chapter 5 Status-quo of China's healthcare construction: the context for the case study

5.1 Introduction

This chapter describes research findings regarding the design and construction of healthcare in China, including digitalisation technologies and DfMA strategies, to present a picture of the context of the case study. The results show the uniqueness of Huoshenshan Hospital in general China's healthcare construction industry. Overall, this chapter provides a comprehensive understanding of the status quo of China's healthcare construction, and how it sets the stage for the case study to come.

5.2 Survey responses

The questionnaire, designed with Tencent questionnaire, was distributed by WeChat between 14 October and 19 October 19, 2021. The target group were AEC industry practitioners with experience in healthcare design and construction. A total of 261 questionnaires were received, of which 78 were excluded for being invalid, due to them containing many homogeneous choices, contradictory choices, and/or incomplete choices. After the screening, this research was left with 183 valid questionnaires, representing a response rate of 29%, which is acceptable according to Moser and Kalton (2017), who suggest that response rates of less than 20% or 30% in social surveys may make the results of little value. The average completion time for the survey was 7 minutes and 8 seconds.

As shown in Table 11, the survey responses are divided into five sections, namely institution type, job type, the building stages in which they specialise, the number of years worked, and institution size. The results show that the four dominant institution types are construction contractor (37.7%), designer (18.6%), owner (15.3%) and consulting services (9.8%). About 80 % of the respondents have more than five years' experience, and nearly half have spent 6-10 years in healthcare construction. The survey findings were then followed up with 13 online interviews with selected practitioners from leading healthcare design and construction firms in China.

Table 11 Survey responses

1. Please describe the type of institution you are working for		
Options	**Percentage%**	**Total**
Owner	15.30%	28
Designer	18.60%	34
Consulting service	9.80%	18
Construction contractor	37.70%	69
Construction equipment supplier	4.90%	9
Medical equipment supplier	3.30%	6
Decoration material supplier	1.60%	3
Operation service provider	4.90%	9
Other____	3.80%	7
Total		183

2. Please describe your job type		
Options	**Percentage %**	**Total**
Pre-planning of hospital projects	5.50%	10
Hospital equipment configuration and management	4.90%	9
Project planning and design	23.50%	43
Hospital engineering construction	24.00%	44
Project implementation management	31.10%	57
Hospital operation management	4.90%	9
Other____	6.00%	11
Total		183

3. What stages of healthcare construction your institution is mainly involved in?		
Options	**Percentage %**	**Total**
Planning	30.10%	55

Design	41.50%	76
Manufacture	15.80%	29
Construction	54.60%	100
Operation	19.70%	36
Other____	3.80%	7
Total		183

4. How many years have you been in the AEC industry?		
Options	**Percentage %**	**Total**
0-5	20.80%	38
6-10.	46.40%	85
11-15.	18.60%	34
16-20	5.50%	10
> 20	8.70%	16
Total		183

5. What is the size of your institution?		
Options	**Percentage %**	**Total**
Miniature (1-10)	2.70%	5
Small (11-50)	22.40%	41
Medium (51-250)	43.70%	80
Large (> 250)	31.10%	57
Total		183

5.3 Findings of DfMA strategies in healthcare construction

5.3.1 OSC in healthcare construction

As the concept of DfMA is rarely used in China's AEC industry, the survey firstly explores OSC, a more popular DfMA-like concept in China, to understand the context of DfMA strategies. According to China's government documents, the questionnaire defines OSC as the replacement of scattered, low-level, and low-efficiency handicraft production methods in the traditional AEC industry with modern production methods of manufacturing, transportation, installation, and scientific management. This definition approximates the OSC interpretation propagated by the Chinese government and therefore fits with the understanding of local practitioners. Its main hallmarks are the standardisation of architectural design, factory-based production of components and parts, construction mechanisation, and scientific organisation and management. A five-point rating scale (see Figure 13) was used to measure the views of healthcare practitioners on the OSC adopted in their institutions' projects. Seven strategies were selected, in line with the OSC interpretation propagated by the Chinese government.

Standardisation is widely adopted as a strategy to promote the OSC of healthcare construction projects, and this can be achieved through a standardised approach to either building design with an average scores of 2.85 or building component systems (2.75). Building design received the highest scores in terms of the standardisation of production, while building component systems means the establishment of a set of standardised components before starting the design phase to engender a standardised approach that utilises these pre-designed components. Using information systems for the whole production process, adopting an on-site assembly method, developing prefabricated building systems, and factory-based component production, were all rated around 2.5-2.7, which shows these strategies were often employed. However, automation in construction by machinery and robotics received low scores around all options (2.03), showing the vast potential for healthcare construction projects to adopt automation and robotics.

(See Figure 13 on the next page)

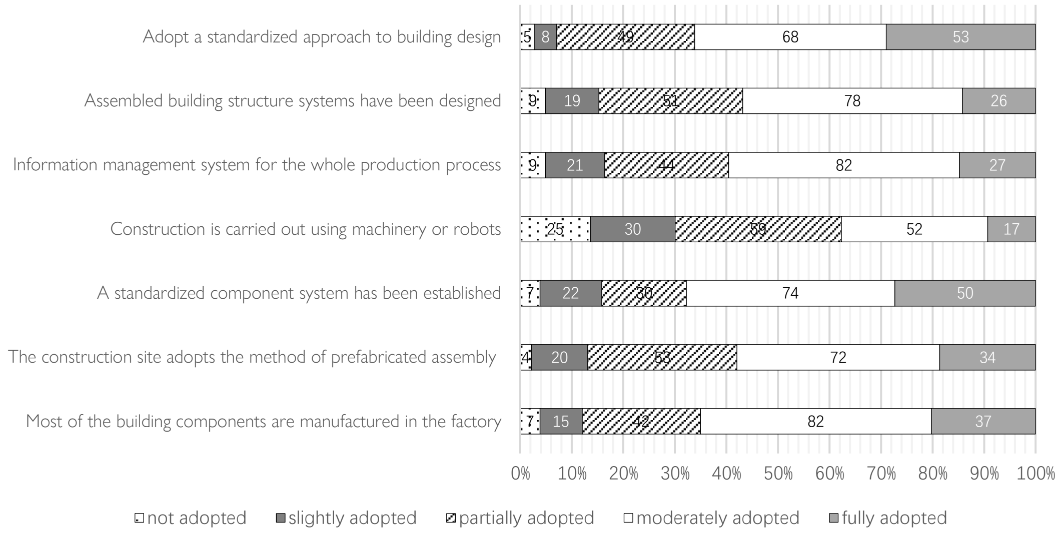


Figure 13 OSC adopted in healthcare construction projects

5.3.2 DfMA strategies implemented to facilitate healthcare construction

This sub-section investigates the DfMA strategies perceived by healthcare building practitioners in their OSC projects, scoring 0-4 on a 5-point scale. The options in the questionnaire were collected through a literature review of construction-oriented DfMA guidelines and strategies. Of the various DfMA strategies, those related to reducing the complexity of the design process, such as selecting environmentally friendly materials, using standardised components and connections, error checking of designs, and improving error tolerances, are relatively easy to adopt and implement because they do not require additional and excessive investment at the design phase (see Figure 14). Techniques that focus on the assembly process and consider the use of building elements that are easy to handle at the assembly stage have also gained much attention.

However, many measures that require additional design tasks are relatively difficult to implement. In modular design, for example, designing multifunctional and multipurpose parts or building elements, and minimising the number of connecting parts, requires thorough consideration by designers and engineers at a very detailed level. Therefore, the requirements for design collaboration and construction quality are high. In addition, the design's impact on the manufacturing stage is generally less considered as a measure to drive DfMA. For example, strategies that design for a mechanised or automated assembly, and that design for the simplified manufacturing of building components, tend to be less considered.

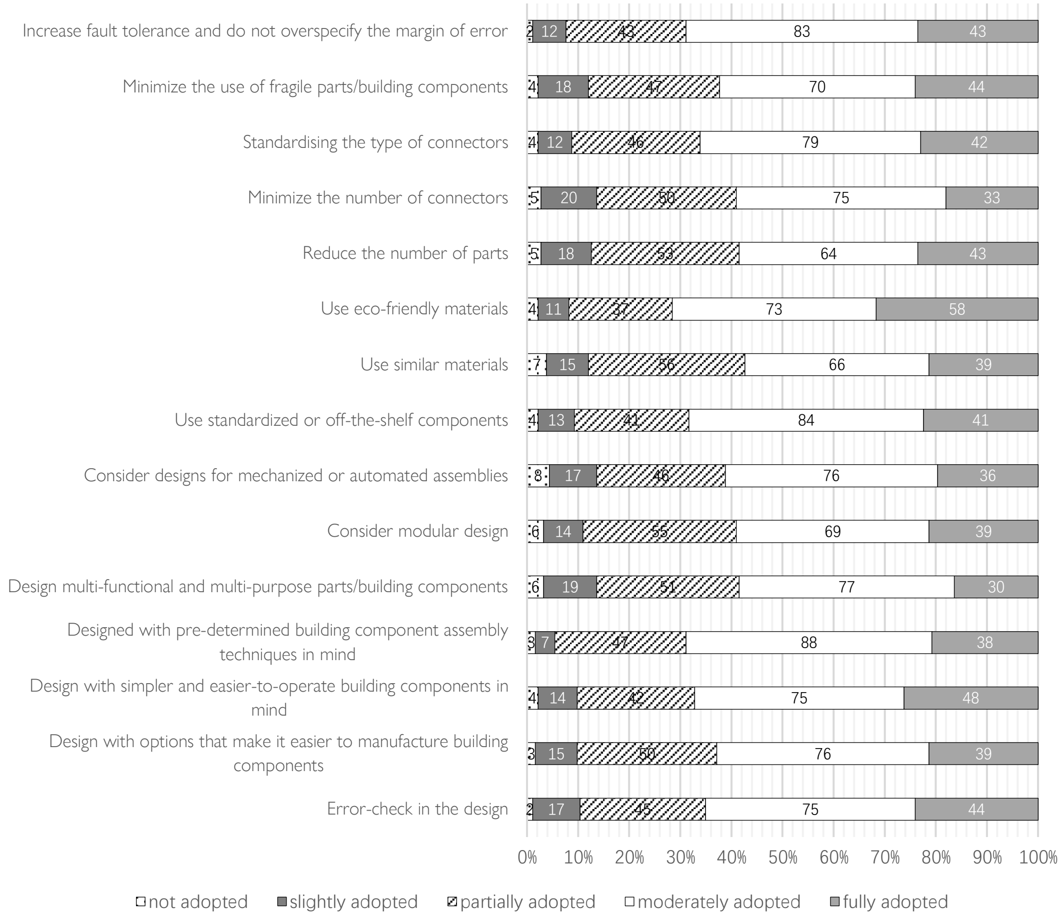


Figure 14 DfMA strategies adopted for healthcare construction projects

5.3.3 Popularity of OSC strategies

This research seeks to understand the prevalence of OSC strategies in the healthcare construction field, using a range of five options to investigate the proportion of projects implementing OSC in the respondent's organisation. For example, the proportion of '0-20%' in the figure means around 0-20% of projects in their institutes have adopted OSC strategies. The number below the proportion means how many participants have voted for that option of proportion. Thus, as shown in Figure 15, very few companies have adopted OSC in most projects. For more than half of the companies, fewer than 50% of their healthcare construction projects implemented OSC, and a considerable proportion of them does not adopt relevant strategies to enhance the level of industrialisation. One of the interviewees, P09, a HVAC leader, said, '*There are not a lot of real OSC in Beijing, especially in healthcare construction*'.

This survey also enabled a cross-analysis to explore the level of adoption of OSC at different building stages. As shown in Figure 16, there were more OSC adopted and implemented during the manufacturing stage of healthcare construction projects; specifically, more than half of the projects in more than half of the institutions adopted OSC, and about half of the institutions adopted OSC in the planning stage in more than half of their projects. Relatively few projects employ OSC strategies during the design, assembly, and operational phases, and it is particularly uncommon to deploy them during the operational phase.

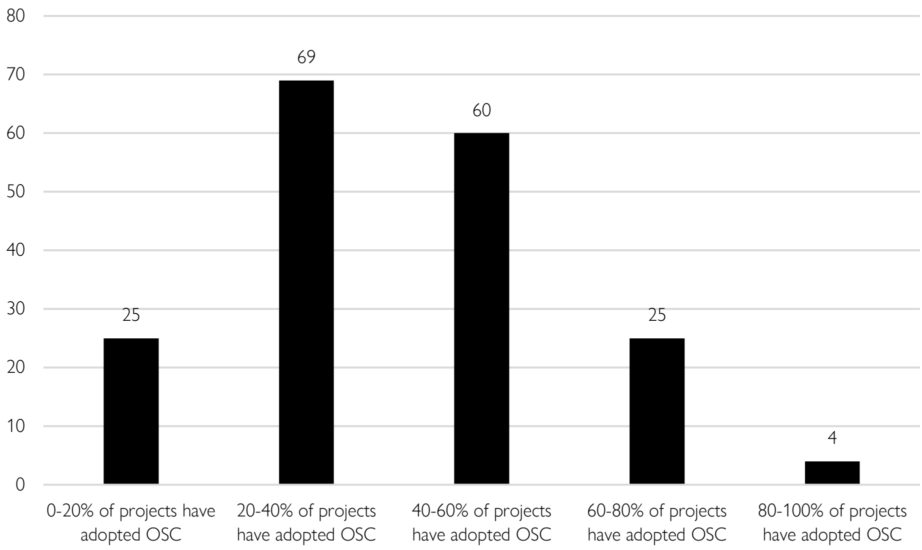
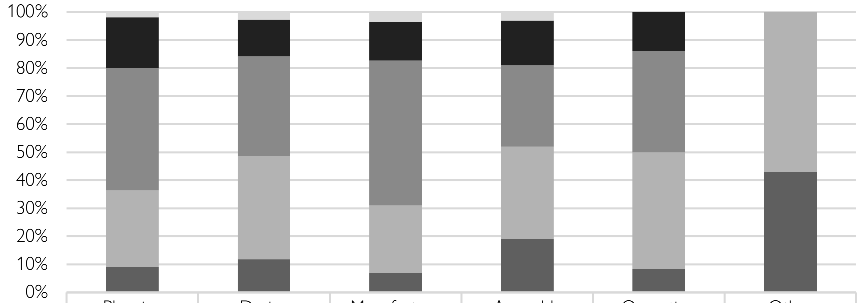


Figure 15 Popularity of OSC strategies



	Planning	Design	Manufacture	Assembly	Operation	Other
80-100%	1	2	1	3	0	0
60-80%	10	10	4	16	5	0
40-60%	24	27	15	29	13	0
20-40%	15	28	7	33	15	4
0-20%	5	9	2	19	3	3

0-20% 20-40% 40-60% 60-80% 80-100%

Figure 16 Popularity of OSC strategies in different building stages

5.3.4 Consequences of the implementation of OSC

This research investigates the consequences of the implementation of OSC from six dimensions, namely 1) reducing labour costs; 2) enhancing production safety; 3) improving product quality; 4) reducing construction duration; 5) reducing resource waste; and 6) reducing the cost of construction. A rating scale was used to measure the consequence of implementing OSC from -2, 'strongly disagree', to +2, 'strongly agree' (see Figure 17). The results suggest that, at the quality and safety level, OSC are perceived to significantly contribute to healthcare construction. In terms of construction duration, resource consumption, and labour costs, OSC has shown some positive impacts. In the survey, the most obvious result is that the current OSC do not offer sufficient advantages in terms of cost and, according to some practitioners, they may even have a strongly negative effect and actually increase costs.

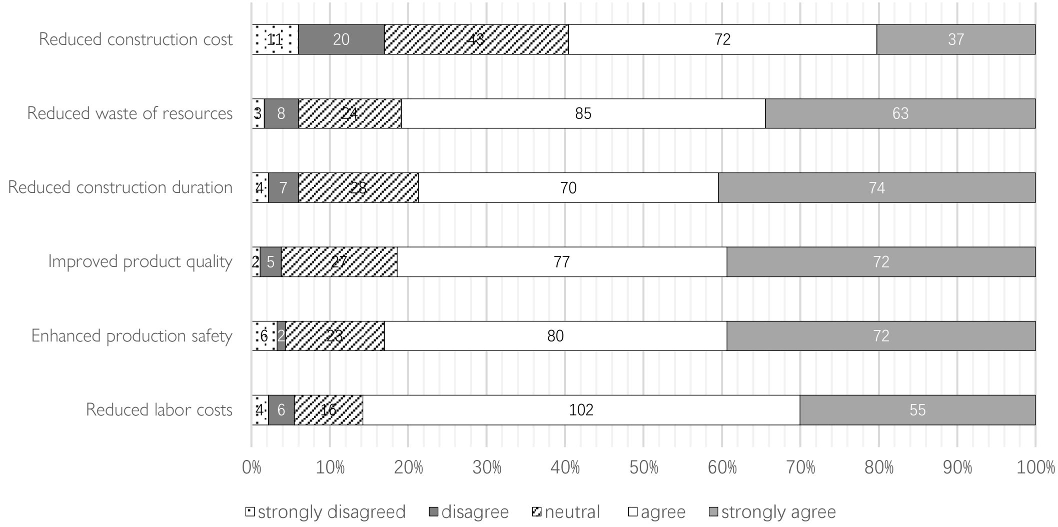


Figure 17 Consequences of the implementation of OSC

5.3.5 Adoption factors for OSC

The results suggest that adopting OSC may be hindered in many ways (see Figure 18). The difficulty of adoption is mainly concentrated on the specific application level of OSC. For example, many practitioners recognise the technical challenges around OSC in the field of healthcare construction, and this kind of challenge hinders their promotion. The second lowest score is for the complexity of the various professional synergy mechanisms around OSC, demonstrating that the adoption of such strategies in the field of healthcare construction involves the collaboration of multiple disciplines. For example, P09, a HVAC leader, said;

> *From the design to the final assembly stage of healthcare construction, the client adjusts the medical process again and again, according to the use needs of each medical department. Every medical process adjustment results in an entire professional design adjustment. Since the OSC is processed and assembled at one time, the split design volume at this time will be larger for the designers*.

This collaborative work is challenged and made more complex by the adoption of OSC, which also interacts and co-exists with the previously mentioned complexity of technical difficulty. OSC also score low in terms of continuous investment and software and hardware support, which shows that many practitioners believe that there is a lack of sufficient funds, software, and hardware to solve the aforementioned problems in healthcare construction. In the interview, P07, a drainage engineering leader, said, '…*because it is still the promotion period, including the selection of its related technologies, may not be very mature. Or there are not so many options on the market,. so the cost may be relatively high now'*.

Not only the lack of financial support, but also the lack of performance of OSC in terms of revenue growth, contributed to the relatively low score for this adoption factor. At the same time, many practitioners believe that clients are not motivated to adopt OSC. The factors driving the adoption of OSC mainly come from three aspects. The first is the company level, where practitioners widely agree that adopting relevant strategies can enhance their competitiveness. Secondly, at the project level, where improving quality and production efficiency are important drivers of adoption. The third aspect is at the policy level, that is, the adoption of OSC is a trend requirement of policy and the industry as a whole.

Despite recognising the role of OSC in COVID-19 emergency healthcare facilities, the findings reveal that many practitioners remain sceptical about the applicability of OSC to major complex hospitals. For example, the survey results implicate that three main factors, namely cost barriers, the complexity of adoption and healthcare uniqueness may be reasons for this attitude. The results show that complexity mainly involves twofold aspects: the complexity of the OSC technology itself and the complexity of the required collaboration for implementing DfMA. The former is primarily a technical issue, while the latter is a socio-technical challenge. Solving the complexities of the technology itself depends on developing and improving the entire DfMA supply chain in the healthcare construction field, which would also contribute to the reduction of adoption costs. Thus, a critical challenge is understanding and reducing the complexity of collaboration in the DfMA practices of healthcare construction.

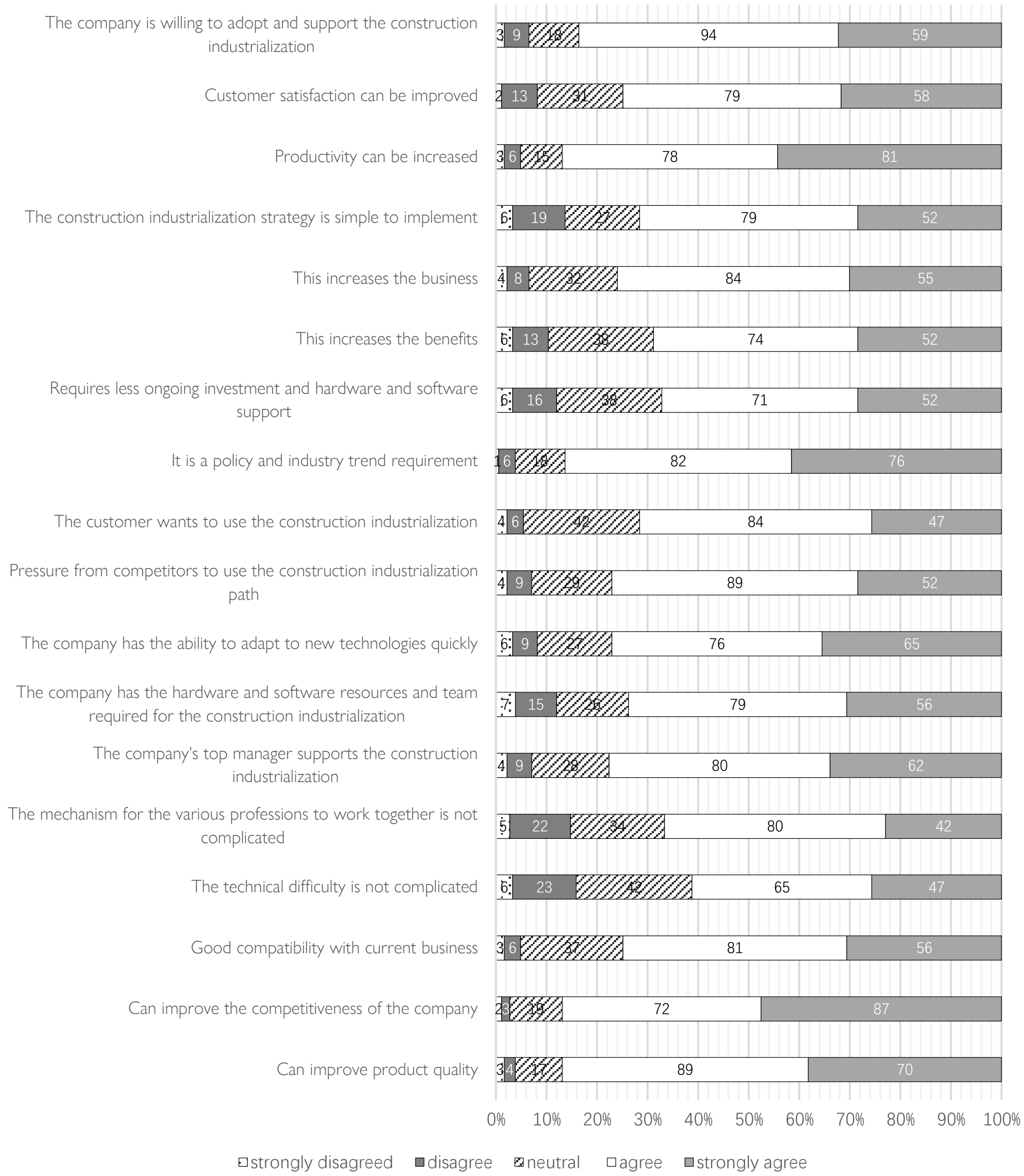


Figure 18 Adoption factors for OSC

5.3.6 Attitudes toward OSC adoption

This research then investigates the attitudes of healthcare construction practitioners towards the adoption of OSC, initially by investigating the differences in the ways in which OSC are perceived by practitioners in Healthcare facilities and other building types, to understand whether there is a need for OSC that is different for healthcare construction projects. This hypothesis serves as a premise and basis for understanding practitioners' attitudes towards adopting OSC specific to Healthcare facilities. This research see from the results that most practitioners believe that, in past practice, Healthcare facilities have adopted OSC that are different from other building types (see Figure 19). However, there are still a small number who have reservations or objections to this difference. For example, a structural lead, P05 said, '*In fact, there is not much difference in terms of DfMA approaches for OSC. They are all designed in the normal way used for traditional buildings*'. About 90% of practitioners believe it is necessary to improve the level of industrialisation in Healthcare facilities (see Figure 20), while over 10% take the opposite position. For example, interviewee P01, an architect lead, highlighted; '*We think that concrete OSC actually have a lot of limitations for hospitals ...... so we generally advise our clients against it'*. P05, a structural leader, said that;

> *Because, from the bottom of our hearts, we still reject it. Anyway, I personally think that even if the policy is to promote OSC, it is not necessary to apply it to hospitals because hospitals are actually a people's livelihood project or a lifeline project, and OSC, as an experimental thing, may not be suitable.*

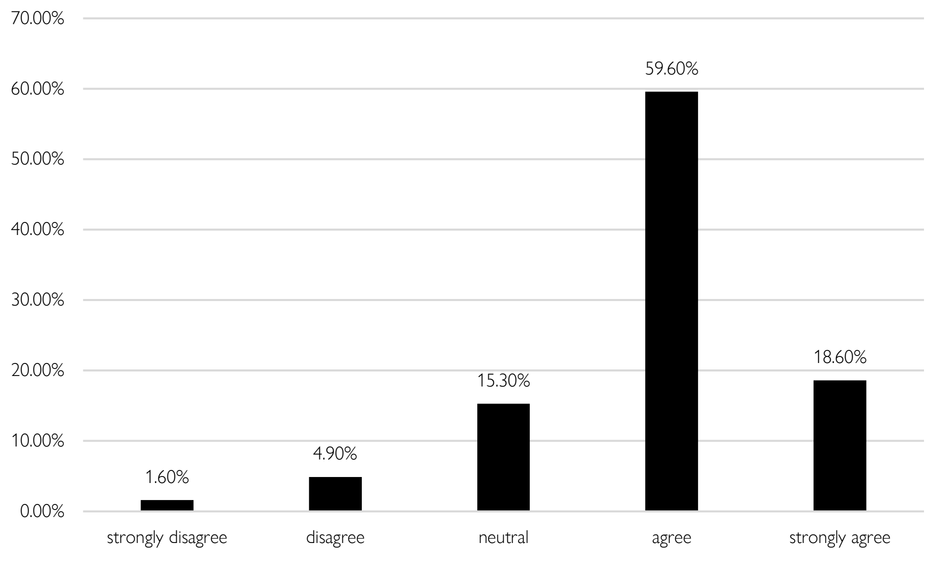


Figure 19 Institutions have adopted a different approach to OSC in healthcare construction than other building types (e.g., residential, office buildings)

To enhance DfMA, it is essential to understand the perceived measures and status of DfMA in current practices rather than theoretical expectations. This section shows that 1) the implementation of DfMA is still in its infant stage in China's healthcare construction and 2) the perceived measures from practitioners might deviate from the essences of DfMA, which poses challenges to the building systems integration due to unmatured adoptions.

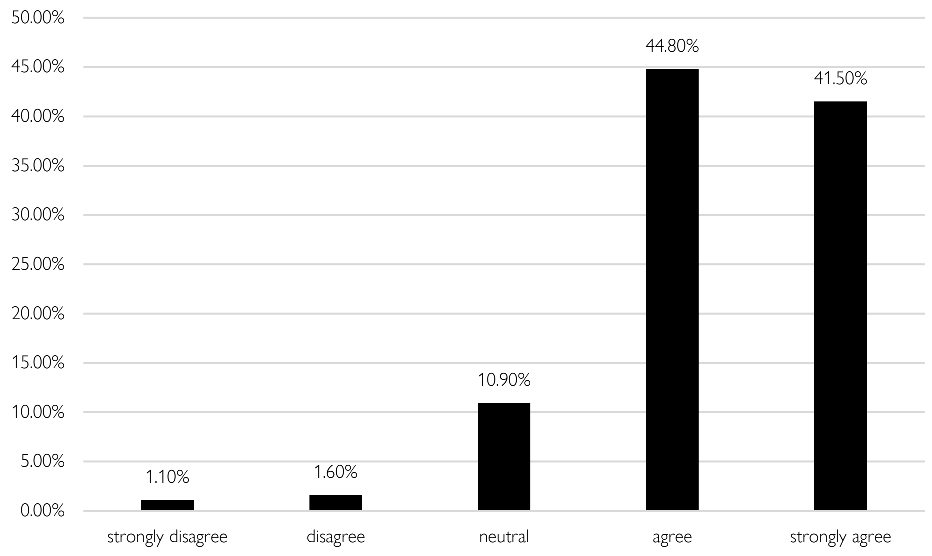


Figure 20 The necessity to increase the proportion of OSC in healthcare construction

5.4 Findings of digital technology strategies in healthcare construction

5.4.1 Digital technologies used in healthcare construction

A five-point rating scale (see Figure 21) was used to measure the healthcare practitioners' views on the digital technologies adopted in their projects. Ten technologies were set for selection, from which this research see BIM is the most adopted technology by a significant margin. Others above the median (2) are 5G networks (2.56), cloud computing (2.28), and IoT/sensors (2.34), all of which have also been adopted across the entire healthcare construction process. By contrast, six technologies were scored below the median, namely artificial intelligence/machine learning (1.86), VR/AR (1.97), 3D printing/additive manufacturing (1.8), blockchain (1.84), digital twin (1.73) and robot (arm)/drone (1.84). These technologies are rarely adopted in the current healthcare construction life cycle.

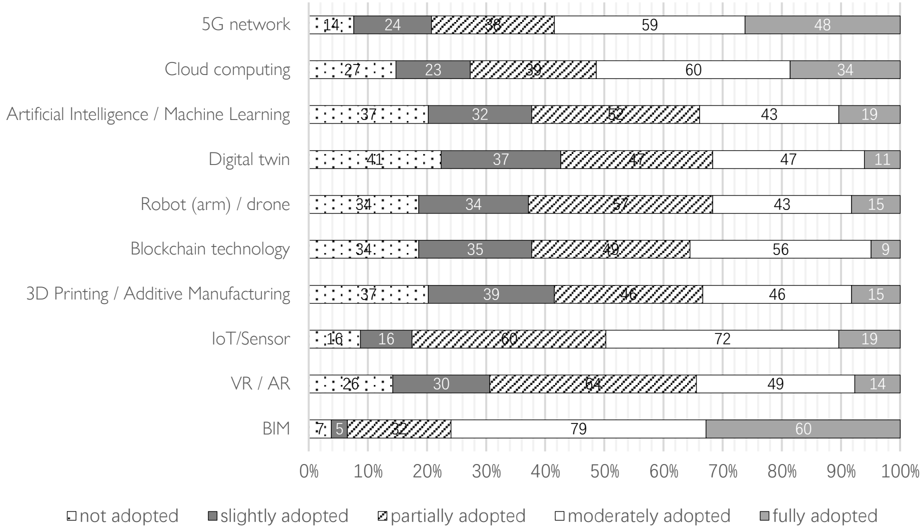


Figure 21 Digital technologies used in healthcare construction

The research results show that BIM attracts the most attention in healthcare construction and far outstrips other digital technologies. While BIM is mandatory in implementing healthcare design in many countries, BIM is not widely adopted in China's healthcare construction. The research finding reveals that the use of BIM in healthcare construction is still underdeveloped in China. Furthermore, the results reveal that other technologies, such as 3D printing and robotics, are far from being adopted.

5.4.2 Popularity of digital technologies

This research attempts to understand the prevalence of digital technologies in the healthcare construction sector, using a range of five options, to investigate the proportion of projects in the institutions of the respondents that implement digital technologies. As shown in Figure 22, digital technologies have been adopted in less than half of the projects covered, and a considerable proportion of the companies may never adopt the relevant strategies to enhance the level of digitalisation. This research also conducted a cross-analysis to explore the level of adoption of digital technologies in different building stages. As shown in Figure 23, more than half of the projects in more than half of the institutions adopted digital technologies during the planning and manufacturing stage, while relatively few adopted digital technologies during the design, assembly and operation phases, which mirrors the picture regarding OSC. The adoption of such technologies in the operation stage is particularly uncommon.

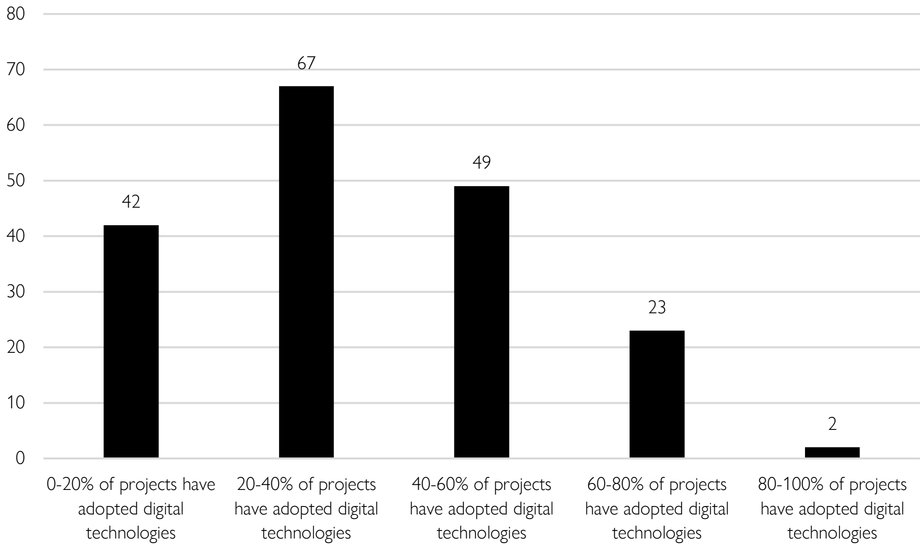
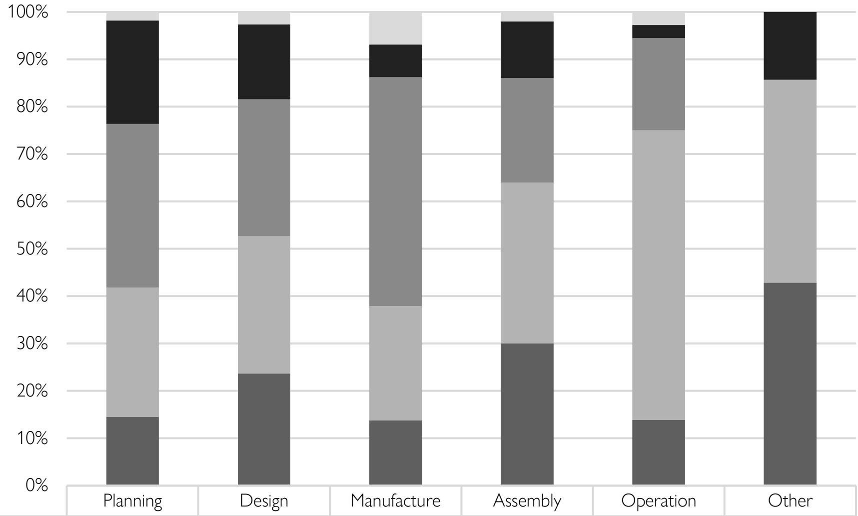


Figure 22 Popularity of digital technologies



	Planning	Design	Manufacture	Assembly	Operation	Other
80-100%	1	2	2	2	1	0
60-80%	12	12	2	12	1	1
40-60%	19	22	14	22	7	0
20-40%	15	22	7	34	22	3
0-20%	8	18	4	30	5	3

0-20% 20-40% 40-60% 60-80% 80-100%

Figure 23 Popularity of digital technologies in different building stages

5.4.3 Consequences of the implementation of digital technologies

This research investigated the consequences of implementing digital technologies across six dimensions, namely 1) reducing labour costs; 2) enhancing production safety; 3) improving product quality; 4) reducing construction duration; 5) reducing resource waste; and 6) reducing the cost of construction. A rating scale was used to measure each one, from -2, 'strongly disagree' to +2, 'strongly agree' (see Figure 24). There are similar scores for enhancing production safety, improving product quality, reducing construction duration, reducing resource waste, and reducing the cost of construction, demonstrating practitioners' interest in these technologies in improving project performance. However, many clearly believe that the adoption of digital technologies in healthcare construction projects will not significantly help in reducing construction costs and may even have a strongly negative effect and increase costs overall.

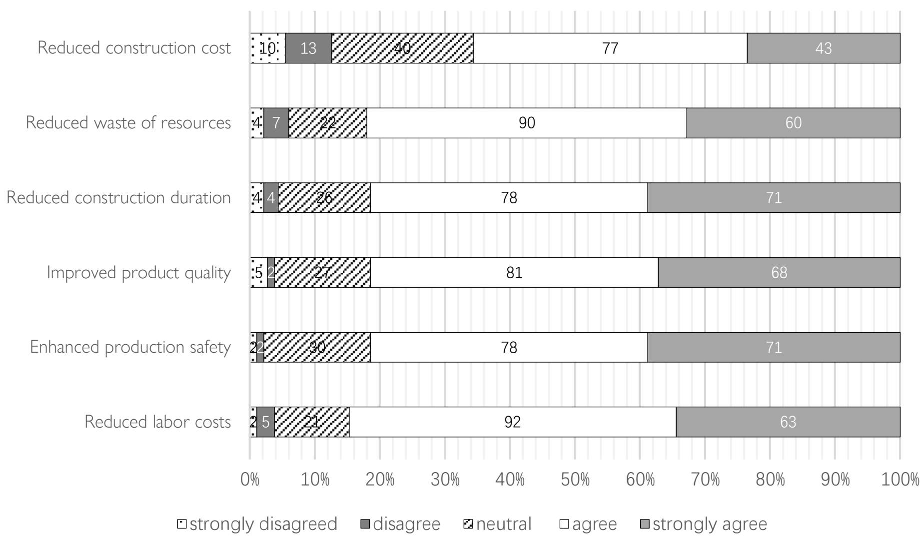


Figure 24 Consequences of the implementation of digital technologies

5.4.4 Adoption factors for BIM

As shown in Figure 25, the distribution of the results for BIM is similar to that of the OSC strategy in many ways. For example, the difficulty of adoption is dependent on the specific application level of BIM; technical difficulty received the lowest score, which shows that many practitioners recognise the technical challenges surrounding BIM in healthcare construction, and these challenges hinder the promotion of BIM strategies. The second worst score is for the complexity of the various professional synergy mechanisms around BIM, demonstrating that the adoption of BIM involves the collaboration of multiple disciplines, which is itself a challenge, and exacerbates the complexity of the technical difficulty cited above. In an interview, P09, a HVAC leader, said that;

> *Just using BIM for building modelling may not be very slow yet, but after all the professions are involved, the model will become bigger and bigger because it has a lot of information in it, so it will be slower to use ...... In fact, it is equivalent to an additional workload*.

The lack of performance of BIM in terms of revenue growth also contributed to the relatively low score for this adoption factor.

Many practitioners believe that clients have little motivation to adopt BIM. Compared with the adoption factor of OSC, there is a relatively low level of support for BIM adoption from the external environment. For example, in terms of continuous investment, and software and hardware support, BIM scored the lowest, which shows the mistrust of practitioners towards BIM adoption in terms of financial support and outcomes. P06, a structural engineering designer, said, '*But the software of structural engineering on BIM is very immature ...... For structural engineering, it is very bad to use at the moment*'. These factors scored the lowest in terms of improving company competitiveness and industry and policy trend requirements. The highest driving factor, on the other hand, comes from improving customer satisfaction, scoring much higher than it did in the adoption of OSC.

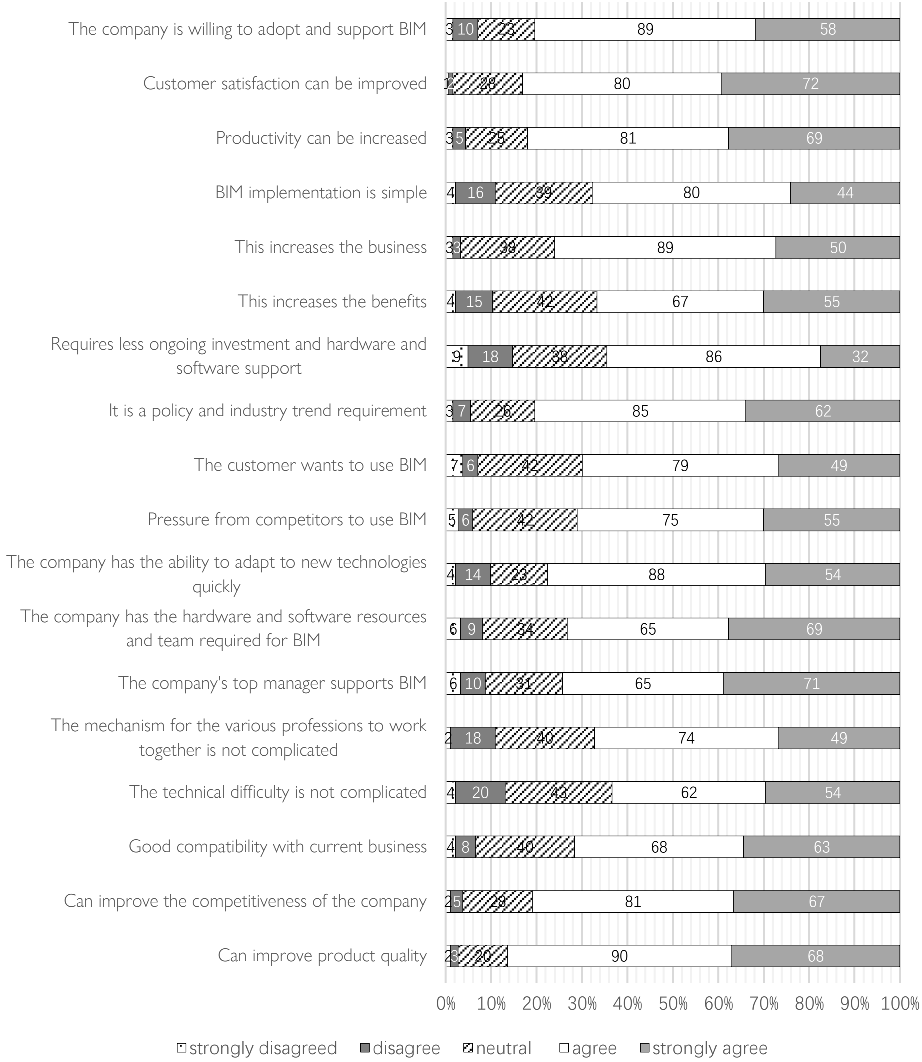


Figure 25 Adoption factors of BIM

5.4.5 Attitudes towards BIM adoption

The research then investigated the attitudes of healthcare construction practitioners towards the adoption of BIM, initially by looking at the differences in the perception of BIM in Healthcare facilities and other building types, to understand whether there is a need for BIM in healthcare that is different from other building types. This hypothesis serves as a premise and basis for understanding practitioners' attitudes towards the adoption of BIM in the specific context of Healthcare facilities. The results show that the vast majority of practitioners believe that healthcare building projects have adopted BIM differently from other building types (see Figure 26), although a small number disagree. In order to improve the level of digitalisation in healthcare facilities, about 87% of practitioners believe it is necessary (see Figure 27), leaving around 13% unconvinced. P06, a structural designer, said;

If it is a very convenient software, everyone will use it without promotion. Now every project is wildly promoting the use of BIM, and yet everyone is still not using it, which means that BIM is not very useful for the project results.

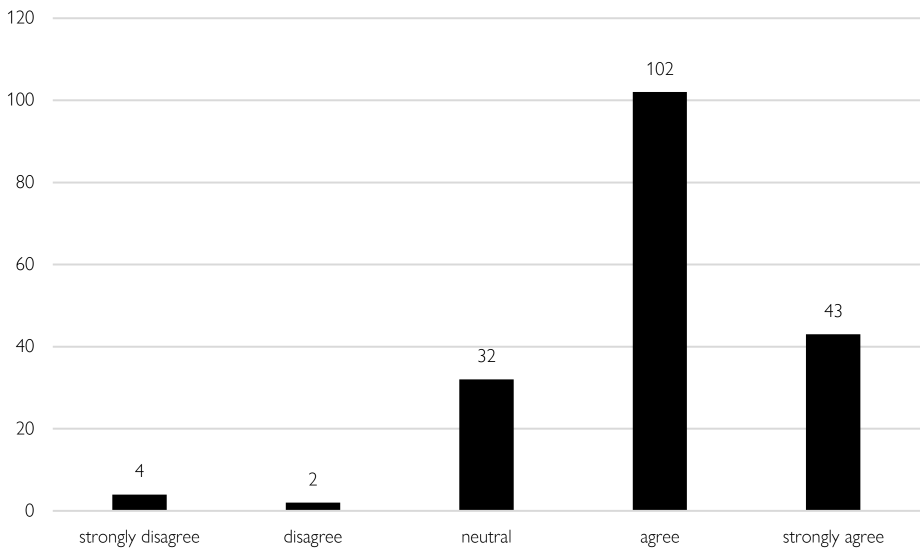


Figure 26 Institutions have adopted a different approach to BIM strategies in healthcare construction than other building types (e.g., residential, office)

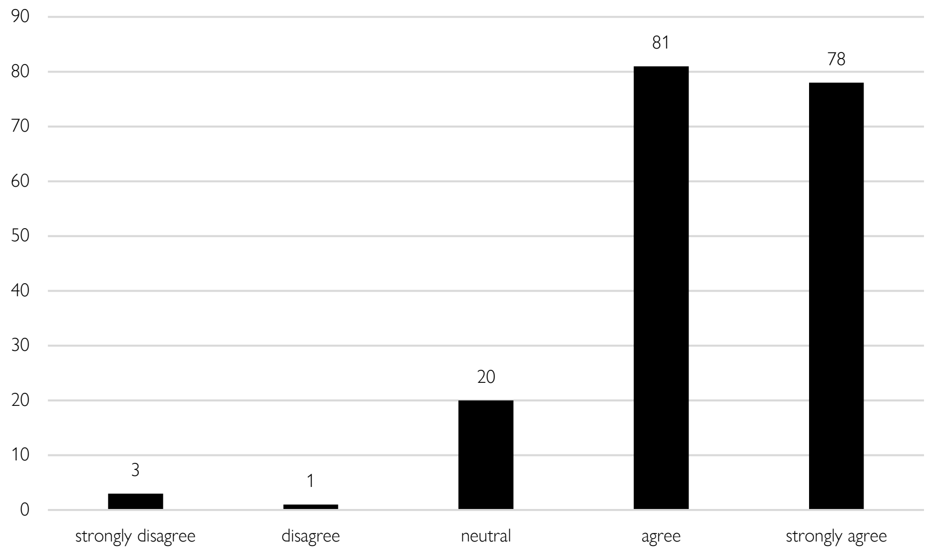


Figure 27 The necessity to increase the proportion of BIM in healthcare construction

Regarding the perceived measures of BIM, the research shows that BIM as a set of digital modelling software has very limited use and gains little trust from China's practitioners in the healthcare design stage. Healthcare construction shows strong public attributes, and most of them are built by the government, and have complex functions and ultra-high investment, making their BIM adoption, different from many other buildings, such as residential, office buildings, etc. The survey results implicate a paradoxical attitude in that the vast majority of practitioners believe that BIM is an important thing for healthcare construction, but do not implement BIM as such in practice.

Besides, the results reveal that practitioners believe that compared to other building types, healthcare construction has unique needs and characteristics for using BIM. The adoption of digital technologies, such as BIM, in healthcare construction, is therefore not only a technical challenge but as same as the nature of the DfMA adoption problem in healthcare construction, is a socio-technical issue which includes the transformation and coordination of the design process, project organisation and supply chain.

5.5 Chapter summary

This chapter presents all results relevant to the industry context of the single case study. According to the results, the research revealed that both BIM and DfMA are at a very early stage of healthcare construction in China, and that the implementation of DfMA and BIM is underdeveloped in the overall industry context and is still being questioned and critiqued. Namely, while recognising digitalisation and DfMA as the future trend in construction, many practitioners hold a critical attitude toward the current industry engaged in digital-enabled DfMA practices. Rather than facilitating project design and construction, many practitioners believe that digital-enabled DfMA may negatively affect the construction of projects, becoming a false act just to satisfy customer or policy requirements.

Chapter 6 Case Study: Huoshenshan Hospital

6.1 Introduction

This chapter presents the DfMA practices that emerged from Huoshenshan Hospital, including the building system categorisations, the DfMA strategies, and the digital-enabled approaches (i.e. BIM) used. Then, this chapter presents the results related to the modularity principles in DfMA, including product, process, organisational, and supply chain modularity.

6.2 Case description: Huoshenshan Hospital

Wuhan, the epicentre of the COVID-19 outbreak in 2020, became the main battleground in the fight against the disease. The daily surge in the number of patients initially overwhelmed Wuhan's medical system, and hospital beds were extremely scarce. There was an urgent need to quickly build a hospital for the treatment of respiratory infectious diseases. On January 23, the Wuhan Government decided to build Huoshenshan Hospital, on the site of the Wuhan Staff Nursing Home, as the first bridgehead against the epidemic. The new hospital, which took the form of a field hospital and adopted a modular design, is located to the west of the sanatorium, with a total land area of about 89,700 square meters and a total construction area of 34,571 square meters (see Figure 28). This is broken down into:

- 15,633 square meters for the first inpatient building;
- 13,788 square meters for the second inpatient building;
- 1,759 square meters for the medical technology building;
- 2,224 square meters for the ICU department; and
- 1,167 square meters for other logistical support rooms.

There are 1,000 beds in the hospital, all serving confirmed COVID-19 cases. The project was completed in just ten days from design to construction, as shown in Table 12 and Figure 29.

Figure 28 Construction site of Huoshenshan Hospital

Table 12 Construction diary

Date	Construction Progress
January 23, 2020	In the afternoon, a team of 60 people from CITIC Design assembled and went to Zhiyin Lake for a site survey. In the evening, multi-party units, including construction, design, and operation companies, held a design coordination meeting. The design work began overnight, and the land-levelling machinery was assembled on site.
January 24, 2020	Completed the site levelling design and made time for the overnight start of construction. The design team completed the scheme design and delivered a scheme report. The construction company cooperated with the design representative at the project site. The designer completed the adjustment of the general layout and the corresponding single building scheme design, based on the newly levelled site, which was then approved by the municipal government.
January 25, 2020	Completed the general plan with construction drawings and structural foundation drawings. Completed general drawing of outdoor water supply, rainwater and sewage infrastructure, outdoor electricals, etc.
January 26, 2020	Completed the first version of the full professional construction drawing design document and delivered it to the construction company.

	The design representative reported the plan to the Wuhan Health Commission Expert Group, the former president of Beijing Xiaotangshan Hospital, and others. The expert group put forward opinions and suggestions. According to the comments and suggestions, the construction drawing design was revised.
January 27, 2020	Completed the full professional construction drawing design documents and delivered them to the construction department. Site levelling was completed, anti-seepage and the pouring of the reinforced concrete foundation began, and the first batch of box-type slab wards was hoisted and constructed.
January 28, 2020	The foundation for the box-type board house in the north of the site was basically completed. The laying of the underground pipe network commenced. The steel structure of the first double-storey ward was completed.
January 29, 2020	The foundation pouring of the box-type board ward is nearing completion. More than 300 panel ward skeletons have been installed. About 400 off-site prefab wards have been spliced together. The hoisting of the rainwater treatment integrated pump station was completed. Materials such as water, electricity, HVAC, and electromechanical equipment were fully in place and construction began in earnest.
January 30, 2020	The laying of the HDPE impermeable membrane was fully completed. The civil foundation work of the box-type transformer was completed. The design leaders of each major on-site party communicated with the military unit responsible for taking over the hospital and listened to opinions and suggestions from the operations side.
January 31, 2020	90% of the box-type board wards assembled. The skeleton of the prefab wards was installed, with an area of 3,000 square meters. The equipment hoisting for the sewage treatment room was completed, and the pipeline installation was 80% complete. Huoshenshan Hospital started electrification.
February 1, 2020	A full set of construction drawings and design documents have been optimised and completed, the site foundation construction was complete, and the installation of medical supporting equipment has commenced.
February 2, 2020	Huoshenshan Hospital project was successfully completed and officially delivered to the Joint Logistics Support Force of the People's Liberation Army.

Figure 29 Completion of Huoshenshan Hospital (source: CITIC)

Due to the Spring Festival holiday, human and material resources were relatively limited, and this became a major challenge for the project. The topography of the original site provided by the planning department was surveyed and mapped many years ago, thus there is no current data. It was neither square nor flat, and was not ideally suitable for rapid construction, thus increasing the design challenges, in addition to the target construction time of just ten days, which required the simultaneous construction of multiple units. These issues had to be considered in advance in the design, and corresponding countermeasures prepared; nevertheless, all these issues still caused great uncertainty and many construction errors.

Huoshenshan Hospital imposes stricter measures than ordinary infectious disease hospitals in the layout of medical zoning and the flow of people. A fishbone-shaped layout with a central axis was adopted, offering the advantages of standardisation, modularisation, and continuous extension according to requirements. The number of modules, and the length of each care unit, can be adjusted according to the site topography and the existing facilities on site, and each nursing unit is an independent standard module, which is conducive to concurrent construction. Each module can be built independently to then be spliced into the overall design to minimise cross-operations. Each until can be completely sealed and isolated in an emergency, such as a deterioration in the epidemic situation, to protect other units in the hospital.

The project adopted off-site technology because the prefabricated structures have the advantages of rapid installation, ease to transport, energy-saving, environmentally friendly, and a high level of on-site adaptability. The standardisation of unit modules, systems integration, assembly of module structures, and off-site technology additionally provides composability and replicability. The box-type prefab ward (see Figure 30) has a lighter load-bearing requirement on the foundations, which greatly simplified the design and construction of the building foundations, reducing the construction period, and maximising the modularisation and industrialisation of the project. The construction of Huoshenshan Hospital was a great example demonstrating the potential of DfMA in China's healthcare construction.

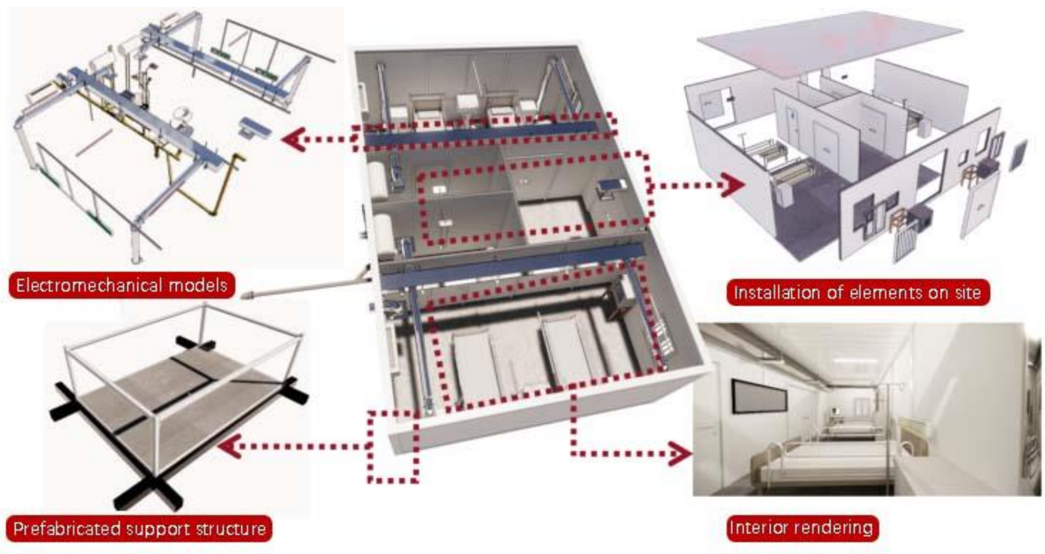


Figure 30 Box-type prefab ward (source: CITIC)

6.3 Building system categorisations

6.3.1 Building systems integration in Huoshenshan Hospital

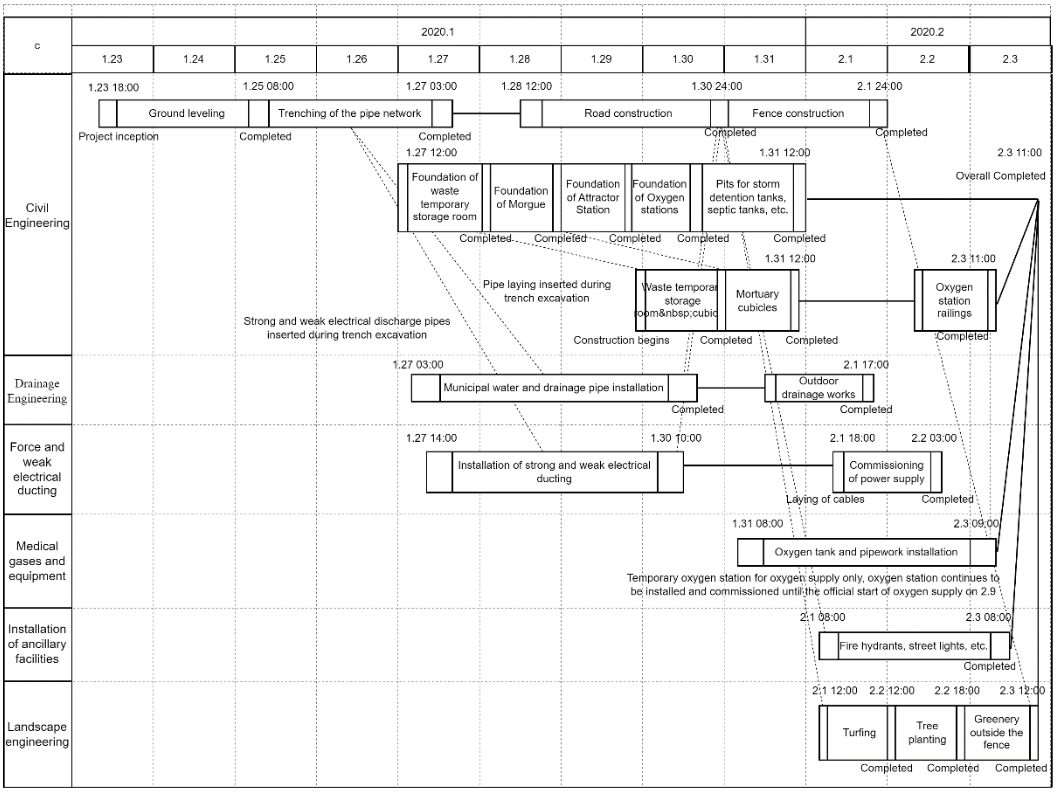
As shown in Table 13, there are seven major engineering systems for Huoshenshan Hospital, specifically architectural design, structural engineering, ventilation and air conditioning, electrical engineering, water supply and sewerage, intelligent engineering, and medical gases.

As shown in Table 14, the construction process of these seven systems was interrelated, and they also worked interrelatedly for the building systems integration and in terms of occupancy safety. They all have sub-systems and unique characteristics when compared with normal building projects.

Table 13 Building systems in Huoshenshan Hospital

Aggregate dimensions	**Code/super code**	**Second Code**
Building systems	Architectural design	Building streamline system
		Building function system
	Structural engineering	Foundation system
		Structural system
	Ventilation and air conditioning engineering	Air conditioning system
		Ventilation system
		Smoke control system
		Control system
	Electrical engineering	Electricity distribution system
		Lightning protection and grounding system
		Illumination system
		Fire alarm system
	Water supply and sewerage engineering	Water supply system
		Sewerage system
		Rainwater system
		Firefighting system
	Intelligent engineering	Information application system
		Intelligent integrated system
		Information facility system
		Security system
	Medical gases engineering	Medical oxygen system
		Medical vacuum system
		Gas monitoring control system
		Medical nitrogen system

Table 14 Construction collaboration and schedule (Chen, 2020)



6.3.2 Architectural system

Architectural design has two sub-systems: building streamline the system and building function system. Since COVID-19 spread so quickly and widely, Huoshenshan Hospital imposed stricter measures in terms of medical and streamline design than ordinary infectious disease hospitals. For example, special entrances were designed for ambulances and transfer vehicles to transport patients into the care units. The building streamline system set up a unique pass-through (i.e. sanitary passage room) for healthcare workers to enter and exit the wards.

In the building function system, the entire hospital is laid out in an L-shape, according to the topography, and divided into two major wards, East and West. This was then divided into contaminated, semi-contaminated, and clean areas at the macro level, and was then further subdivided; for example, the semi-contaminated area was divided into the potentially contaminated area and the semi-contaminated area. In this case, the medical staff aisle, located in the middle of the ward unit, is a semi-contaminated area, while the medical staff work area, located between the ward unit and the cleaning area, is defined as a potentially contaminated area. A buffer room is provided at the access point between these two areas where medical staff enter. By dividing the semi-contaminated area into two zones, the medical and nursing staff in the work area are more protected. The final layout is one of ‘three zones and two passages’.

6.3.3 Structural engineering systems

There are two structural engineering systems: the foundation system and the structural system. As an emergency healthcare project, there was no time to make structural selections and technical decisions, as would be the case in a conventional project. Following the site survey, the designers quickly excluded pile foundations, composite foundations, and other forms of foundation that require complex processing, and instead selected natural foundations, mainly choosing raft, strip, and independent foundations. There was a need for an impermeable membrane, so a reinforced concrete raft slab foundation system was finally adopted.

The demand for rapid construction led to the design, manufacturing, and construction parties quickly deciding on the structure through joint discussion, based on the design principles of fast fabrication, convenient transportation, and easy installation, while maintaining safety and reliability. A prefabricated steel structure was chosen for the structural form, creating a mix of box-type rooms and mobile rooms, based on requirements for material type, quantity, and transportation distance at that time. The wards are container-like modular steel assemblies, while the larger rooms, such as the medical technology building and the ICU building, are mobile rooms.

6.3.4 Ventilation and air conditioning system

The ventilation and air conditioning systems include air conditioning, ventilation, smoke control, and a control system. The most significant features that distinguish Healthcare facilities from other buildings are isolation and protection, and therefore the focus of the

HVAC design is to ensure the appropriate pressure relationship between each functional area and to prevent cross-contamination. The ventilation and air conditioning system in Huoshenshan Hospital project also took into full consideration three additional requirements:

1) the air conditioning system takes full account of the local climate and emergency engineering needs;
2) air supplies and exhausts are organised to form pressure gradients to prevent cross-infection between doctors and patients;
3) the number of complete air changes per hour, and the filter installation and replacement protocols, are selected specifically for each ward and protection area.

Integrated design and collaborative construction were very important here. For example, the container roof structure was not strong enough to bear the weight of ventilation and air conditioning equipment, especially when added to other equipment and, at times, construction or maintenance personnel, which could easily lead to excessive force and structural deformation. Furthermore, installing electromechanical equipment on a steel roof structure creates the need for vibration damping and sound insulation. Therefore, in this project, most of the ventilation equipment is on the ground outside the buildings. There was also the issue of waterproofing around roof holes for ventilation ducts. This is difficult in conventional constructions, and even more so with prefabricated box-type buildings, so the ventilation ducts were routed away from the rooves as much as possible, leading to very few roof holes being required.

6.3.5 Electrical engineering systems

The electrical engineering includes electricity distribution, lightning protection and grounding, illumination, and fire alarm systems. The electrical design of Huoshenshan Hospital fully accounted for the matching of the modular design with the ward units, aiming for rapid replication within the modular units, and maintaining unit independence as much as possible.

6.3.6 Water supply and sewerage engineering system

The water supply and drainage design includes water supply, sewerage, rainwater, and firefighting systems. The drainage design focuses on the standard treatment of medical wastewater and the division into collection and discharge to avoid the build-up of harmful gases. For example, Huoshenshan Hospital zones the drainage system, defining medical and technical buildings, the wards, and the ICU as contaminated areas, so wastewater from the washrooms and bathing areas, and faecal sewage from the contaminated areas, are classified as contaminated. The drainage pipes are independently ventilated, collected and treated centrally in zoning. The site rainwater is collected and discharged centrally.

6.3.7 Intelligent engineering system

Intelligent engineering includes the information application system, the intelligent integrated system, the information facility system, and security. The information application system consists of the waiting call signalling system, special medical information, and the nursing call signalling system. The information facility system includes the telephone exchange, the network, integrated wiring, and the public address system. The security system includes video monitoring, entrance/exit control, electronic patrol, and parking management. The integration of these intelligent systems also faced many challenges, not least of which was the fact that the construction of these systems had to be completed in only two days. In addition, intelligence engineering involved many construction units, and problems inevitably arose.

6.3.8 Medical gases engineering system

Medical gas engineering consists of medical oxygen, medical vacuum, gas monitoring control, and medical nitrogen systems. Medical gases are partly an essential life support system that is essential in the construction of modern hospitals. The medical vacuum system sucks up the patient’s sputum, pus, blood, and other dirty waste fluids and deposits them into a waste fluid bottle or bag. A small amount of liquid dirt enters the collector in the medical vacuum station through the pipes, and the gases are discharged, so the medical vacuum system is one of the important potential sources of hospital infection. In Huoshenshan Hospital, the oxygen system uses the remote level and pressure monitoring to ensure safe operation. The medical nitrogen system includes the busbar, pipelines, and gas point equipment.

6.4 DfMA strategies

6.4.1 Challenges to design

Through the triangulation of interviews and documentation sources (see section 4.6.3), this section inductively summarises the challenges to the use of DfMA that mainly involve design and design management (see Table 15). In design, these are:

(1) healthcare process complexity;

(2) functional complexity;

(3) design resource constraints;

(4) safety requirements;

(5) lack of experience;

(6) site constraints; and

(7) design fault tolerance.

In terms of design management, the challenges are:

(1) time limitations;

(2) change of stakeholders;

(3) many stakeholders;

(4) lack of staff; and

(5) lack of suppliers.

There are a total of 12 super codes, and 37 main challenges (second codes) to successfully implementing DfMA. Time and material constraints were among the key challenging factors mentioned by all interviewees. When designing Huoshenshan Hospital, the design institute needed to complete the drawings as quickly as possible to ensure the organisation and construction of resources on site. Safety requirements were also emphasised by almost all interviewees. As an emergency project of great social significance, and in the context of a public health emergency, the design needed to fully consider patient treatment and survival systems, and ensure the safety of medical and nursing staff, with high, strict standards for infectious disease control. Subsequent digital technologies and DfMA strategies attempted to address these challenges in various ways, thereby driving the integration and delivery of building systems.

Table 15 Challenges to design

Aggregate dimensions	Code/super codes	Second Code
Design	Healthcare process complexity	Difficulty in the healthcare process
		Complication in design and construction processes
		Partial adoption of prefabrication
		Many design tasks
	Functional complexity	Many functional requirements
		Many building systems
	Design resource constraints	Use of off-the-shelf materials on the market as building materials
		Use of building materials with short processing time (usually about two days)
	Safety requirements	Infectious disease control
		Environmental needs
		Emergency safety needs
	Lack of experience	Lack of experience in architectural design of prefabricated hospitals
		Lack of design experience in emergency engineering
		Lack of design standards
	Site constraints	Inaccurate site information and outdated geomatic data
		Uneven terrain

		Limited land available
		The site included ponds, ravines, and small temporary buildings
	Design fault tolerance	Uncertainty of design accuracy requirements
		The designers cannot fully access on-site information
		Requires more construction tolerances
Design management	Time limitation	Short design time
		Design-construction coordination requires a lot of time
	Change of stakeholders	Change of operations party
		Change of ownership
		Temporary team organisation
		Team personnel changes
	Many stakeholders	Many types of design disciplines
		Complexity of drawing/information delivery
		Responsibilities unclear between stakeholders
		Lots of design opinions, but a lack of decision-making capabilities
		Conflict of design opinions
	Lack of staff	During the Spring Festival holiday, many people are out of work and visiting their hometown
		Huge demand for personnel
	Lack of supplies	Heavy logistical support required by personnel
		Use only medical and construction equipment that is available in the short term
		Only use building materials that are available in the short term

6.4.2 Implementation of DfMA

This section presents the aggregated results to document a set of DfMA strategies from the case study. As shown in Table 16, there are 17 main design strategies which are then inductively classified into five categories: modularity, adaptability, flexibility, simplification, and standardisation.

Table 16 Attributes of DfMA and its management strategies

Aggregate dimensions	Code/super codes	Second Code
Design attributes	Modularity	Architectural design follows building modules
		Building is formed by container modules
		Employ modular equipment
	Adaptability	Design functions/equipment adapting to weather changes
	Flexibility	Use multiple connectors with different sizes
		Hand-drawn design on-site to deal with emergencies
	Simplification	Installation adopts simplified procedures and methods
		Minimise adjustments of the construction site
		Consider material supply and construction schedule issues
		Simplify the foundations design
		Design based on available construction materials
		Simplify design standards
		Simplify construction technique processes
		Assemble container modules off-site
		Follow temporary building standards
	Standardisation	Use standard modules
		Use standard interfaces

Simplification represents the functionalism of the project, and designing to a strict set of building requirements was the priority. These requirements looked to maximise the capability of the hospital to respond to COVID-19, rather than any aesthetic, cultural, or architectural attributes; for example, as mentioned by many interviewees, the primary goal was to meet the bed requirements. Inventory-based design is one of the most significant ways to achieve simplification. Due to the limited construction time, the building was designed based on what the contractor and suppliers had in the inventory to simplify and reduce the manufacturing process, instead of following the traditional DfMA path. In addition, many functional and design requirements could be simplified as the building was classified as temporary.

Modularity saves on both design and construction time, especially for complex projects like hospitals, where there are numerous technical sub-systems requiring corresponding knowledge and suppliers. Modularity solved many of these challenges. In this project, the modular wards were assembled by redesigning and retrofitting the mobile houses initially used as temporary homes for the construction workers, and equipment, such as electrical gear, also adopted modularity to reduce on-site installation and deployment times. The concept of modularity was implemented at the organisational level, as well as in the physical modularity of the built products.

Adaptability reflects the construction resilience and ability to respond to on-site uncertainties through early design, allowing the design to cope with the actual on-site situation at any given moment. Prefabrication requires more accurate design and control of the on-site assembly process, compared with conventional on-site wet construction. Due to the construction speed and material inventory, there were challenges with regard to on-site craftsmanship. Many adaptability-related measures, such as design functions and equipment being adapted to weather changes, were undertaken in this project.

Flexibility is a coordination mechanism that allows for rapid design changes in light of the actual construction situation. Flexibility and adaptability create resilience. The difference between these two concepts is whether the design is changed to cope with the real situation. Flexibility focuses more on design changes. The project demonstrated the value of flexibility in several different ways; for example, hand-drawn designs were used on-site to deal with emergencies, and multiple connectors with different sizes were used to solve accuracy problems.

Standardisation has been recognised as an effective strategy for the construction sector. However, it is also challenging to accomplish. The critical challenge is to balance the trade-off between standardisation and flexibility, as the former can undermine construction resilience. However, the similar requirements across many buildings and functional components for the hospital provided an opportunity for design standardisation.

6.5 Digital-enabled approach strategies

6.5.1 The current usage of digital technologies

In Huoshenshan Hospital project, the use of digital technology in the design process to aid in design optimisation was very limited. For many design sections and disciplines, there was no use of advanced digital technologies, such as BIM tools. For example, interviewees from almost all disciplines emphasised that the use of CAD drafting, the most traditional design software, was still the most dominant tool during the design of Huoshenshan. Second, many of the design decisions were made by experts from various disciplines, rather than through digital technologies and, from a design evaluation and optimisation perspective, Huoshenshan Hospital project did not demonstrate a unique advantage in digitalisation using BIM modelling, but rather adopted a traditional drafting approach, similar to many typical Chinese hospital projects.

In the wake of Huoshenshan Hospital, many places in China and other countries chose to build temporary emergency hospitals and retrofit projects in response to COVID-19 so after the project was completed, the BIM department within the design team drew up a new BIM model of Huoshenshan Hospital and conducted various design evaluation and optimisation simulations to review the design plan. This post-event review of the design was a form of ‘post-occupancy evaluation’, and it fed into the effectiveness of the design and management of similar projects and had a positive effect on the dissemination of Huoshenshan Hospital experience.

In contrast to the low degree of digital technology application in design optimisation, digital technology for design management presents a very unique feature that is not an exemplary representation of the widespread use of software, or the popular application of new digital technologies, but rather a reflection of the efficiency of applying digital tools to manage design information at times of high information requirements and density. In Huoshenshan Hospital, the digital tools for design information management, such as WeChat, online meetings, and 5G networks, are already very common in various work scenarios and are in no way unique. Instead, the project was characterised by a high-density information scenario within a unique collaborative environment, and the embodied information communication mechanisms developed organically.

There are three aspects of information communication mechanisms that are reflected. The first is the channel of communication. For example, Huoshenshan Hospital project tried to comprehensively collate the information of the personnel in all design disciplines and create an address book to facilitate communication through WeChat and QQ groups. More important information was communicated through SMS, email, paper documents and so on, while urgent information was communicated by telephone, conveyed in person, or agreed upon in meetings. The second aspect is the division of the information communication hierarchy. Information was divided according to the degree of importance and confidentiality, and was further divided into a decision-making level and an execution level. The third aspect is the refinement of the scope of information communication. For example, the establishment of a general contracting management group, a logistical support group, a resource coordination group, a technical quality group, a traffic coordination group, and so on, by speciality and position, was implemented to effectively achieve timely and effective communications.

6.5.2 Barriers against the use of digital technologies

The majority of the interviewees indicated that there was very limited adoption of digital technology in Huoshenshan Hospital project's design stage. Therefore, as shown in Table 17, this research analysed four main factors that hinder the implementation of digital technologies, namely time limitations, adoption complexity, lack of demand and incentives, and negative adoption attitudes. One of the most significant factors hindering the adoption of digital technologies, such as BIM, is time limitation, a factor mentioned by almost all interviewees. Since Huoshenshan Hospital was built in a very short period, there were only 1-2 days to complete the design for many of the engineering systems. The adoption of digital technologies such as BIM, for example, not only goes against the design firm's traditional CAD-based production model, but designers also need time to learn and adapt to the application of BIM technology.

Table 17 Barriers against the use of digital technologies in design

Aggregate dimensions	Code/super codes	Second Code
Barriers against the use of digital technologies in design	Time limitations	Only 1-2 days to complete the design
		Adopting BIM takes a lot of time
		Limited effect of improving the speed of design completion
	Adoption complexity	It is difficult to adopt digital technology across the whole supply chain
		Adoption of digital technology requires additional hardware and software support
		The use of digital technology is not compatibility with the traditional production methods of design companies
	Lack of demand and incentive	Lack of incentive for commercial profit
		Lack of incentives driven by managers
		Lack of policy-driven incentives
		Lack of incentives for customer needs
	Negative adoption attitudes	The idea that digital technology cannot efficiently solve engineering design problems
		The idea that digital technology cannot efficiently solve engineering management problems

Many interviewees also indicated that digital technologies like BIM are not effective in improving design completion times. There is also a lack of demand and incentive. Since

Huoshenshan Hospital is a public health emergency project in the face of a major pandemic, there were no commercial interests driving it. All policies and management were geared towards the rapid and safe completion of the project, so the adoption of digital technology in the design process was not a prerequisite, nor was it the highest priority to be considered in the design. Given the challenges associated with digital adoption, such as the need for additional hardware and software resources, and the lack of a mature BIM application across the supply chain, a rash adoption of BIM would have presented many challenges to the project and contributed to the negative attitude of the design team towards the adoption of digital technologies. For example, many interviewees felt that the adoption of BIM would not bring visible results to the project's engineering design and design management.

6.6 Modularity principles in design

6.6.1 Product modularity in Huoshenshan Hospital

Product modularity corresponds to 'modularity-in-design', and is a product design strategy using standardised and interchangeable components for the configuration of various products (Schilling, 2000). The design process of Huoshenshan Hospital embodied the idea of product modularity in many ways. In this research, two categories, namely function proximity and component proximity, are used to summarise the measures of product modularity (see Table 18). Function proximity is the closeness of the modules within a product or system structure, of which there are three: partitioning of building layouts, partitioning of hygiene layout, and partitioning of the site layout. For example, the site also posed a challenge to designers due to the multiple construction teams working in parallel, and they had to design and strategise for multiple parallel construction situations in advance of construction work starting. The site is on a slope, so the designers divided it into two terraces (i.e. two modules) and also divided the building into two major parts according to the site, leaving sufficient spacing at the junction and connecting only with access roads (i.e. interfaces). The height difference between the two terraces was later adjusted several times according to the construction conditions but without any impact on the overall design.

Component proximity means the physical closeness of the modules within a product or system structure. There are also three ways to achieve component proximity, which are keeping the same type of components/equipment used in one area, the use of modular building components/equipment, and minimised equipment-to-building interfaces and openings. The standardised interface was not used as a strategy for product modularity; instead, a non-standardised interface strategy was used to increase design variability, improve construction fault tolerance, and reduce construction workloads. For example, at the container joints, the designers built in different seam widths at the interfaces to handle construction errors.

Table 18 Product modularity in Huoshenshan Hospital

Aggregate dimensions	Code/super codes	Second Code	Descriptions/Examples
Product modularity	Function proximity (i.e. functional closeness of the modules within a product or system structure)	Partition of building layout	The Partition of building layout divides the hospital into zones based on function, such as patient care, diagnostics, and administration. Areas are arranged in close proximity to allow seamless coordination between hospital departments.
		Partition of hygiene layout	The Partition of hygiene layout involved separating high-risk and low-risk areas, using physical barriers to prevent the spread of pathogens, creating designated entry and exit points, and implementing regular cleaning and disinfection protocols.
		Partition of site layout	It was crucial due to the challenging terrain, which required significant modifications before construction

		could begin. By partitioning the site into functional zones, the construction team minimised the need for modifications and improved efficiency.
Component proximity (i.e. physical closeness of the modules within a product or system structure)	Same type of components/equipment used in one area	This contributed to that each area module had the same or similar medical equipment, layout, and configuration of patient rooms, staff areas, and support facilities for consistency and efficiency.
	Use of modular building components/equipment	It contributed to streamline the production process, reduce costs, and ensure that the hospital units could be easily transported and rapidly assembled on site.
	Reduced equipment-to-building interfaces and openings	This design approach minimised the number of physical connections between the hospital equipment and the building structure, which helped to reduce the risk of contamination and improve the overall safety of the hospital.

6.6.2 Process modularity in Huoshenshan Hospital

Process modularity, mainly used for planning purposes, describes the degree to which a process can be decomposed into modules for parallel execution (Parraguez et al., 2019), and corresponds to 'modularity-in-production'. Specifically, process modularity standardises manufacturing sub-processes so they can be easily re-sequenced or swapped out for new modules, sometimes known as 'plug-and-play' (Tu et al., 2004). Huoshenshan Hospital design deployed process modularity through two characteristics, including task proximity and technological proximity, can be used to explore process modularity deployed in Huoshenshan Hospital design (see Table 19).

Table 19 Process modularity in Huoshenshan Hospital

Aggregate dimensions	Code/super codes	Second Code	Descriptions/Examples
Process modularity	Task proximity (i.e. the degree to which different tasks or activities within a process are related or interconnected)	Concurrent design process between interdisciplinary teams	One aspect of this process was the design-proofreading-reviewing concurrent process, which involved three people working together on a single computer monitor to design and review simultaneously. This allowed for rapid iterations of the design, with each team member providing input and feedback in real-time.
		Standardised/modularised design tasks	By sorting out complex medical processes, classifying tasks for functional rooms, optimising mechanical and electrical systems, and integrating equipment and pipelines, it enabled the realisation of standardised/modularised design tasks, which facilitated the overall design process.
	Technological proximity (i.e. the degree to which different modules or components of a process share common technologies or technical infrastructure)	Collaborative design process by involving manufacturers	This process involved working closely with manufacturers of building materials, medical equipment, and other supplies to ensure that their products were integrated seamlessly into the hospital's design.
		Collaborative design process by involving purchasers/suppliers	For example, the design team worked closely with medical equipment suppliers to ensure that

		the hospital's layout and infrastructure were optimised for the use of the equipment. This involved considering factors such as the size and weight of the equipment, as well as its power and ventilation requirements.
	Collaborative design process by involving contractors	Contractors were involved in the design process from the early stages, providing input on constructability, sequencing, and material availability, among other factors.

Task proximity means the degree to which different tasks or activities within a process are related or interconnected. For example, all design professionals deployed a design-proofreading-reviewing concurrent process, whereby three people are designing in front of one computer monitor at the same time, working on all three paths simultaneously. Secondly, the total functional space of the hospital was standardised and divided by sorting out complex medical processes, classifying functional rooms, optimising mechanical and electrical systems, and integrating equipment and pipelines, thus realising standardised design tasks. Then, the corresponding generalised and modularised design tasks were carried out using the selected materials and electromechanical equipment.

Technological proximity means the degree to which different modules or components of a process share common technologies or technical infrastructure. The construction side appointed technicians to participate in the design process, and the procurement team provided feedback to the design team on the equipment and materials that could be procured, who then designed to the principle of ‘use what is available’. The material specifications of different manufacturers varied, so it was necessary to deepen the design according to the actual size of products. The design team also appointed a designer to be on site to guide the construction according to the design, and feed back to the design team. The design of the prefabricated components, and the module production and processing drawings of the construction side, were carried out simultaneously, and the production and assembly process requirements were fed back to the design team in a timely manner, which then leveraged the synergy between design and factory production, professional suppliers, and on-site assembly, and provided a fundamental guarantee for shortening the construction period.

6.6.3 Organisational modularity in Huoshenshan Hospital

Through the data analysis, three project organisation strategies were identified by three codes, namely responsibility proximity, knowledge proximity, and resource proximity (see Table 20). Responsibility proximity indicates the degree to which individuals or teams within an organisation share common responsibilities. Firstly, members of multi-enterprise teams integrate in order to work together. All disciplines within the CITIC had corresponding designers from different contractors to work together, and all contractor disciplines had corresponding on-site designers from the CITIC (see Figure 31). This hybrid structure promoted sharing of common responsibilities between temporary organisations. Healthcare buildings are among the most complex public buildings, and building systems for handling infectious diseases further increase complexity. This project involved many technical disciplines, far exceeding those required for ordinary buildings. Extensive communication, penetration, and integration (i.e. information and knowledge sharing) between multi-discipline teams were critical to this project.

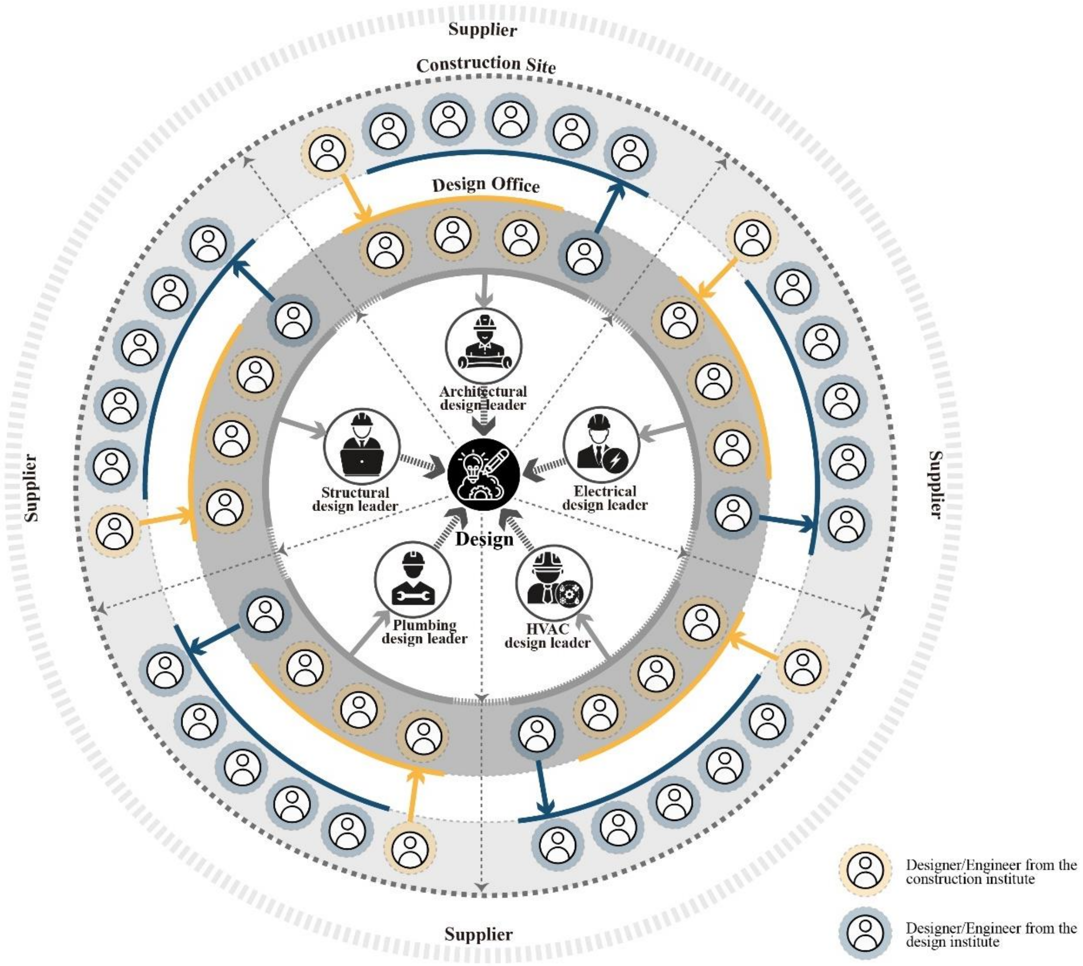


Figure 31 Collaborative design organisations in Huoshenshan Hospital

Knowledge proximity indicates the degree to which different individuals or teams within an organisation share common knowledge or expertise. For example, a 24-hour shift schedule, high-density information exchange, daily meetings and decision-making were all adopted. It is worth noting that advanced design and communication technologies, such as BIM software, were not used at the design stage. Collaboration was achieved through very conventional methods, including telephone and WeChat group communication, sharing screenshots and pictures, and SketchUp/AutoCAD drawings. The designers on this project all have rich work experiences and have engaged in a long-term cooperation. And the CITIC and main contractor are all local companies with long-term cooperative relations, which contributed to quickly establishing collaboration to share common knowledge or expertise.

Table 20 Organisational modularity in Huoshenshan Hospital

Aggregate dimensions	Code/super codes	Second Codes	Descriptions/Examples
Organisational modularity	Responsibility proximity (i.e. the degree to which individuals or teams within an organisation share common responsibilities)	Different design disciplines all have designers from the main contractor	Each of these design disciplines had designers from the main contractor, who worked collaboratively to ensure that the hospital was designed and built in a manner that met the needs of the project.
		Different design disciplines all have on-site designers	On-site designers were physically present at the construction site, working closely with the construction team to ensure that the design is implemented correctly and any issues that arise during construction are addressed in a timely manner.
		Purchase team members work with designers directly	The purchase team members worked directly with the designers to ensure that the necessary materials and equipment were sourced and purchased in a timely and efficient manner.
		Collaborative decision-making to minimise changes	To achieve this goal, the design team, including designers from different disciplines and the construction team, worked collaboratively to ensure that all design decisions were thoroughly discussed and agreed upon before implementation.
	Knowledge proximity (i.e. the degree to which different individuals or teams	Different design disciplines all have potential design	A design interface refers to the point where the design of one discipline meets and affects the design of another discipline.

within an organisation share common knowledge or expertise)	interfaces for other professionals	
	Work in double shifts (24*7)	The 24*7 work schedule allowed the project to progress quickly and efficiently, with the design and construction teams working around the clock to meet the tight deadline.
	Instant online communication and daily meetings	The teams used instant online communication tools such as messaging apps and video conferencing to stay in touch throughout the project.
Resource proximity (i.e. the degree to which different individuals or teams of an organisation share common resources)	Different design disciplines all have designers work at the construction site	It promoted a more efficient use of on-site resources between design and construction teams to share common resources such as tools, equipment, and materials.
	Different design disciplines from the main contractor work at the office of the design institute	It promoted a more efficient use of design resources between design and construction teams to share common resources such as software, drawings, and specifications.

Resource proximity indicates the degree to which different individuals or teams of an organisation share common resources. There were many pieces of evidence from this project about high resource proximity; for example, construction began on the site from the moment the design started; the on-site designers worked with contractors at the construction site and created on-site designs based on actual construction situations; and the contractor was involved in the early decision-making with design institutes, the government, and healthcare operators. Different design professionals from the main contractor work at the office of the design institute directly.

6.6.4 Supply chain modularity in Huoshenshan Hospital

Supply chain modularity emphasises the interdependence within, and independence across, certain supply functions or tasks, and refers to whether certain supply functions or tasks are conducted by a single supplier and whether they can be explicitly distinguished from others (Wolters, 2002), thus aiming to mitigate the complexity within supply chain coordination. The design of Huoshenshan Hospital embodied supply chain modularity through the three ways identified by (Voordijk et al., 2006), namely geographic, organisational, and cultural proximity. Although geographic proximity can be measured by physical distance (Voordijk et al., 2006), time was a more appropriate indicator for Huoshenshan Hospital project. For example, the design only selected equipment and building materials that were close at hand and could be transported to the site in a short period of time. In addition, due to the Spring Festival, the project team only brought in personnel from Wuhan to quickly build temporary teams.

Organisational proximity deals with ownership, managerial control, and interpersonal and inter-team interdependencies (Voordijk et al., 2006). In this case, three main approaches represented organisational proximity, namely collaborative alliance, central or state-owned enterprises, and government organisations (see Table 21). For example, the design and construction companies were mainly central or state-owned enterprises. The Party Committee hosted many project promotion meetings at the construction site, supervised the project, guided the project construction work in the field, coordinated and solved key issues, and fully guaranteed the completion of the project. Many specialised companies working under the China State Construction Engineering Corporation (CSCEC) quickly participated and embedded in the specific business aspects of the construction of Huoshenshan Hospital. Represented by the China Construction Third Engineering Bureau Co. Ltd., the main impetus for the integration of its subordinate enterprises and sister engineering bureaus came from the top-down internal authority of the enterprise. The main integration impetus between CSCEC and other sister central enterprises came from the administrative power of the State-owned

Assets Supervision and Administration Commission of the State Council. Cultural proximity captures the commonality of language, business mores, ethical standards, and laws, among other elements (Voordijk et al., 2006).

The supply chain integration at Huoshenshan Hospital was driven by both internal and external state-owned enterprises, with the internal manifestation being a corporate culture with a sense of social responsibility as the core of the main body of the industrial chain, and the external manifestation showing hierarchical characteristics, from top to bottom, in the order of administrative power and internal corporate authority.

Table 21 Supply chain modularity in Huoshenshan Hospital

Aggregate dimensions	Code/super codes	Second Code	Descriptions/Examples
Supply chain modularity	Geographic proximity (i.e. physical distance between different entities within a supply chain)	Local sourcing for equipment and building materials	the design team chose equipment and building materials that could be sourced locally and transported to the site quickly for the local climate and environment, reducing the risk of construction issues or delays.
		Temporary local teams	To rapidly construct Huoshenshan Hospital, personnel in Wuhan were mobilised to form temporary teams. This approach allowed for the efficient allocation of resources and the quick formation of specialized teams.
	Organisational proximity (i.e. the degree of closeness between these entities in terms of organisational structure or relationships)	Collaborative alliances	These alliances involved government agencies, hospitals, universities, and private companies, who worked together to share resources, expertise, and knowledge.
		Central or state-owned enterprises	These enterprises, which are owned by the Chinese government, were able to provide the necessary financial and logistical support required for the project's success. They

		were able to mobilise resources quickly and efficiently, including personnel, equipment, and materials, to ensure that the hospital was constructed in a timely manner.
	Government organisations	The Huoshenshan Hospital was a massive undertaking that required the combined efforts of multiple government organisations and thousands of individuals to ensure its completion within the tight timeframe.
Cultural proximity (i.e. the degree of closeness between different entities in terms of their cultural norms, values, beliefs, and practices)	Culture of state-owned enterprises	One of the key cultural traits of state-owned enterprises in China is a strong sense of commitment to public service. Another cultural trait of state-owned enterprises in China is a focus on efficiency and results. The sense of duty to public service and focus on efficiency and results were critical in completing this project in record time.
	Culture of Communist Party of China	The focus on collective good, discipline and order, and innovation and technological development were critical in the rapid completion of the project and in addressing the urgent public health needs of the COVID-19 outbreak.
	Corporate Social Responsibility (CSR)	The design and construction of the Huoshenshan Hospital in Wuhan, China can be viewed as an example of CSR, as it was a project carried out to serve the public good.

6.7 Chapter summary

This chapter presents all results relevant to the single case study, in the context of China's healthcare construction industry, building systems, and DfMA practices in Huoshenshan Hospital, and modularity principles underlying the DfMA strategies. This next chapter discusses these results and answers the research questions.

Chapter 7 Discussion

7.1 Introduction

This chapter discusses three sections, namely 1) improving building systems integration through DfMA; 2) integrated approaches for digital-enabled DfMA; and 3) Reinforcement relationships between multiple dimensions of modularity. This chapter presents these three sections to establish the answer for '*How can digital-enabled DfMA be implemented effectively in healthcare construction through integrated approaches to achieve building systems integration?'*

7.2 Improving building systems integration through DfMA

7.2.1 Building systems as a dynamic hierarchical network

Huoshenshan Hospital is not a typical general hospital. As an emergency respiratory infectious disease hospital, it provided an unique opportunity to understand how design and engineering for therapeutical needs could be adapted to a highly complex situation. The hospital is a showcase for an organisation's building systems integration capabilities, especially the realisation of design. The results of this research revealed seven major building systems in Huoshenshan Hospital (see Figure 32), which correspond to areas of expertise which were embedded in the design process for each of these systems. The process of building systems integration was one in which corresponding design teams formed temporary project-specific organisations through interdependent, collaborative relationships. These relationships shaped the expertise into a final product.

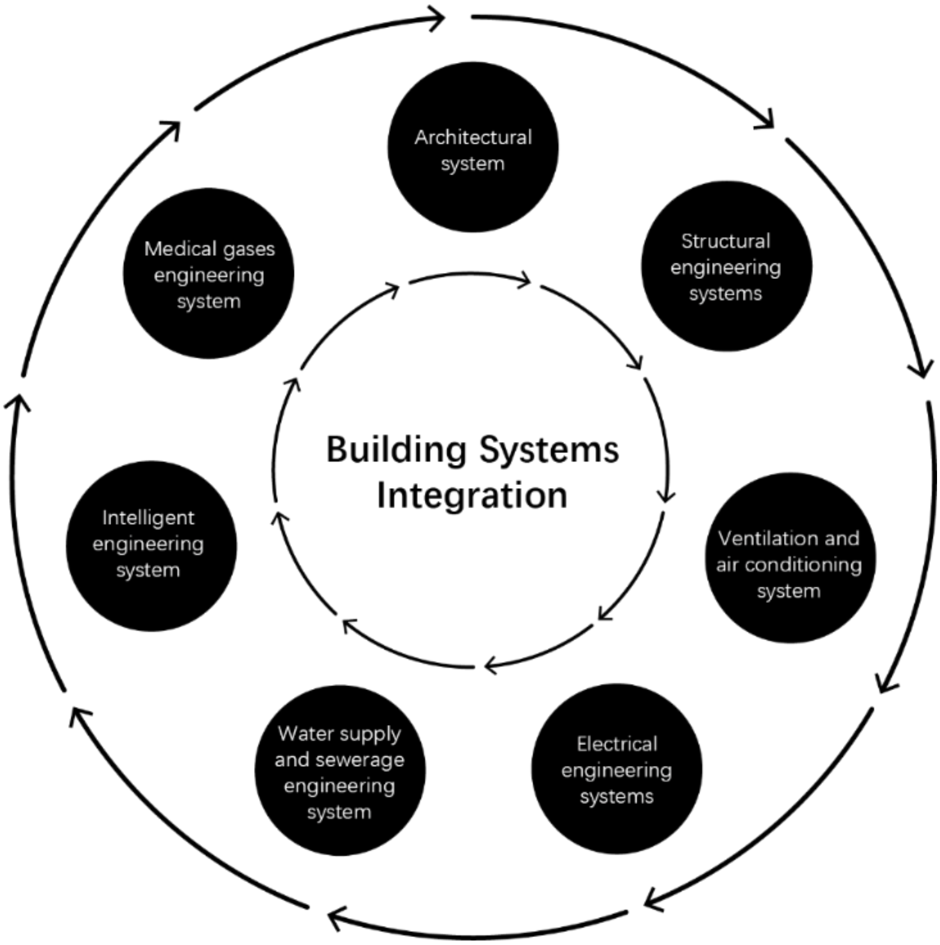


Figure 32 Building systems in Huoshenshan Hospital

There may be a dozen sub-systems within a system, such as the intelligent engineering system (see Table 13). This supports the view that building systems integration is a multi-layered, interrelated system, just like a dynamic hierarchical network. The nature of being a dynamic hierarchical network system brings 37 challenges to DfMA (see Table 15). The results show that strategies, such as using standardised interfaces or simplifying design standards, were used to integrate various sub-systems within the dynamic hierarchical network system (see Table 16). The contribution of this research is to deconstruct the process of integrating building systems using the theory of modularity. Building systems integration through DfMA was observed in a facility that enabled rapid response, expansion of medical capabilities and provided a safe environment (see Table 12). By establishing the nature of the building system as a dynamic hierarchal network, this research extended the basic approach of how to achieve DfMA beyond building systems integration solely at the level of physical components.

7.2.2 Building systems integrator for complexity reduction

Building systems in healthcare construction have a high degree of hierarchical structure. This necessitates a building systems integrator to drive consensus between all parties and reduce complexity in the development and design of building sub-systems and construction paths. The role of the integrator includes defining and integrating the activities of a full range of system inputs. This research further extended the ideas by Wamelink et al. (2012) and Renier and Volker (2008) who advocated for architects to reclaim their central position and facilitate integrated practices by acting as a building systems integrator. The findings showed that architects did coordinate and collaborate on information and products in healthcare construction as well as in other design disciplines. As the systems integrator, this research shows that the role of the architect within the dynamic hierarchical network system is to reduce complexity by reconfiguring abstraction, determining whether to reveal or keep information hidden, and setting up configurable interfaces.

DfMA requires the introduction of downstream knowledge early in the design phase (Gao et al., 2020). As a result, hiding of the individual expertise in design gets reconfigured, and, if needed, exposed. The building system integrator needs to take on the responsibility of framing and managing the configuration process (Renier & Volker, 2008), which is a more important role than designing specific tasks through expertise. With this reconfiguration of knowledge, the responsibilities of the designers of the various disciplines are consequently reconfigured. For example, in Huoshenshan Hospital, there were relatively fewer project interventions by structural engineers. Part of the role of structural engineers moved to that of specialist in supply chains, and manufacturers of modular facilities took responsibility for the structural performance of manufactured products. In addition, the importance of other engineering disciplines increased significantly because the performance of service systems (see Table 13), which have a direct impact on the safety and health of patients and clinicians, is of great concern in healthcare construction.

7.2.2 Challenges of building systems integration

In contrast to traditional DfMA studies, which consider manufacturability and assemblability as an end unto itself (Bogue, 2012), this research found that it was more appropriate to consider manufacturability and assemblability as a measurement of DfMA, and that the ultimate goal should be the integration of building systems, namely the process of bringing together all building components physically and functionally into a coordinated whole. This transformation focuses not only on the physical level of integration, but also on the functional level. Exploring integrated approaches to DfMA for healthcare construction means discovering how to integrate different measures of a design process for healthcare building systems to physically and functionally merge into a coordinated whole. This single case study (on Huoshenshan Hospital) did not aim to propose a one-for-all optimal design strategy. Rather, it attempted to identify the possibilities for relationships between different dimensions of modularity. Through this extreme example, the research identified how these strategies and relationships manifested themselves in DfMA, that is, the ways, means, and impacts that drive building systems integration.

The findings revealed 37 challenges which were a complex combination of multiple factors in the design phase of building systems integration (see Table 15). This research provided new knowledge and insights into the challenges faced in healthcare building systems integration in China. The most striking challenge was the stringent requirements for design and construction schedules brought about by COVID-19. This posed serious threats to the integration of 'software', specifically related to the design process, design organisations, and supply chains during building systems integration.

A major challenge in healthcare construction projects was meeting a schedule (see Table 12), which keeps the budget under control, while a delay can lead to dramatic economic and health-related losses. Nevertheless, project delays are a very common occurrence in many healthcare construction projects (S.-Y. Kim et al., 2016; Mittal et al., 2020). While this phenomenon can ultimately be a serious detriment to the effectiveness of a project, the constraints of design and construction time in a conventional project do not usually seriously affect the DfMA as they did in this case. Huoshenshan Hospital needed to be delivered on time to meet patient capacity, and therefore provided an excellent opportunity to explore what happens when deadline challenges have to be addressed. Constraints on schedule cause serious challenges for cost and quality of building design (Chen & Tang, 2019; Emmitt, 2014). Since cost did not have the highest consideration in this Huoshenshan Hospital project, this research presented a new perspective in building systems integration, i.e. new insights into how design (DfMA) affected building quality.

The second challenge in DfMA was in operational safety (see Table 15), in the requirement for integration of 'hardware' in building systems, namely physical integration, visual integration and performance integration (Bachman, 2004). The complexity of safety, i.e. the need to consider the safety of different users in different scenarios when designing a healthcare project due to the many roles of the users, impacted the goals and methods of implementing of DfMA. Adjusting to these specific scenarios of DfMA requires a detailed understanding of the needs and activities of clinicians and patients. DfMA therefore requires intensive communication and collaboration with the hospital users to understand the requirements of 'hardware' of integration in building systems. Changes made by the owner brought about multiple changes to the safety requirements, which in turn affected the number of design changes and thus created challenges for the implementation of DfMA and building systems integration.

Therefore, identifying the need for safety as early as possible is of great significance in enabling DfMA. These two challenges reflect the operational concerns in healthcare building systems. In a healthcare construction setting, DfMA should, therefore, also focus on the integration of 'hardware' and 'software' in building systems.

7.2.3 Towards building systems integration in digital-enabled DfMA

Regarding the perceived measures of BIM (see 6.5.1 The current usage of digital technologies), this research showed that BIM, as a digital modelling software, was limited in use and in trust by healthcare facility designers in China. Emmitt's (2016) discusses the disconnection of the following two facets of BIM: a set of software for designers to model the design in a virtual environment and a set of information held in one place and used for a building. This research revealed that BIM did not necessarily need to be bundled with a BIM tool, such as Revit. The disconnection between the two facets of BIM was not an erroneous strategy for DfMA in the context of Huoshenshan Hospital.

What was crucial was the effectiveness of DfMA in terms of the adaptation and integration of multi-dimensional information through the disconnection. As a digital collaborative process, BIM enhanced DfMA through the adaptation and integration of information. The results revealed that BIM and DfMA did not directly lead to building systems integration (see 6.4.1 Challenges to design; and 6.5.2 Barriers against the use of digital technologies). In essence, BIM facilitated the managing and optimising of information in the DfMA process, which led to building systems integration. The information was not only from the building product dimension (see Table 18), but also from the process (see Table 19), organisational (see Table 20) and supply chain dimensions (see Table 21), which enabled the adaptation and integration of information from multiple dimensions.

This research presents a novel perspective on the nature of DfMA and BIM, setting aside the typical debates surrounding standardised strategies for DfMA, and Revit-like tools for BIM. DfMA achieves more consensus among practitioners when treated as a strategy to promote building systems integration rather than just a strategy to implement standardisation, and when focusing on BIM as an innovative process to optimise information management rather than software implementation. This shift in focus acknowledges that BIM's true potential lies not just in creating detailed 3D models but in serving as a comprehensive information management and collaboration platform. It facilitates the seamless integration of diverse datasets and supports the dynamic exchange of information among all stakeholders involved. This has a profound impact on the DfMA process, as it ensures that all the necessary data is readily available and can be adapted to suit the specific requirements of each project, thus enabling a more cohesive and effective approach to building systems integration. This is the essence of the pursuit of digital-enabled DfMA. This research therefore proposes integrated approaches, which aim to balance guidelines, strategies and principles of DfMA to achieve the overarching benefits of building systems integration during the design process.

7.3 Integrated approaches for digital-enabled DfMA

7.3.1 Integrations of various digital-enabled DfMA guidelines

Integrated approaches can reconcile conflicts between different strategies, such as various DfMA guidelines, in digital-enabled DfMA. This research extends the understanding of the integration of various DfMA guidelines. Building systems integration strategies can be divided into design management strategy for 'software' integration, and design strategy for 'hardware' integration (Bachman, 2004). Design strategy refers to the rules and guidelines for the engineering and design of specific building components, parts, spaces, and functions, and the relationships between them, and their interdependencies and dependencies. Design strategy focuses on design and development at the product dimension, which is also called the 'hardware' level. Design management strategy refers to the socio-technical 'software' level around which the former strategy revolves, i.e. how to organise activities in order to design to satisfy needs. In terms of design strategies, the case study in this research revealed 17 specific design strategies and five corresponding DfMA attributes (see Table 16). Although other authors such as Vaz-Serra et al. (2021), Chen and Lu (2018) and Bao et al. (2022) have presented case studies and guidelines on DfMA, the attributes behind the strategies/guidelines have not been systematically discussed.

DfMA guidelines may change project-by-project. The construction of Huoshenshan Hospital did not entirely follow the general DfMA guidelines. For example, the project, in some building area, did not widely adopt standardised interfaces between building component (see 6.6.1 Product modularity in Huoshenshan Hospital). The results revealed that the implementation of BIM and DfMA guidelines alone in the Huoshenshan Hospital did not directly lead to building systems integration (see 6.4.2 Implementation of DfMA). The key to meeting the systems integration challenge at Huoshenshan Hospital was coordinating the DfMA guidelines in multiple areas, which compensated for shortcomings in individual areas.

Building systems integration, therefore, is not only the result of a designer's integration of knowledge of individual systems, but also the result of a design system's integration of a series of collaborative processes around a set of hierarchal systems. Simply summarising or generalising DfMA strategies and guidelines from case studies may not validate the results. This research explored the design attributes behind DfMA-related strategies and guidelines (see Table 16). The critical question was and is how DfMA integrates these attributes and what benefits of building systems integration can be achieved.

7.3.2 Modularity for complexity reduction

In building the Huoshenshan Hospital in ten days (see Table 12), it would have been impossible to rely on the traditional stick-built construction method. Modularity principles were widely adopted across the four dimensions of product, process, supply chain and organisation (see Table 18, Table 19, Table 20 and Table 21). These modular principles, which can be used to reduce complexity, reflect the essence of modularity in three facets: (1) abstraction, (2) information hiding, and (3) interfaces (see Figure 7). Hiding information can reduce risks and help designers adapt to new needs based on new knowledge. Although many studies advocate the significance of information exchange and bringing various stakeholders' information to the design stage (Chen et al., 2015), they neglect or does not discuss the information redundancy and intellectual property protection issues. A designer cannot consider all information and requirements. A constant flow of information will make it difficult for designers to make correct judgments and choices. Rather than *more is better*, streamlined and concise information from multiple teams, namely 'lean' information, is more conducive to making good decisions in DfMA.

In engineering projects, especially in healthcare construction, complex stakeholder relationships and unexpected circumstances result in a lot of information and requirements emerging, which leads to frequent subsequent design changes. Although emergence is often used to refer to the appearance of unplanned organised behaviour in a complex system, a conclusion of this research was that information and requirement are a type of 'emergence' during the design process, rather than a fixed object that can be identified and discovered at the beginning. An effective way to combat the need for frequent design changes is through the modularity principle.

To manage complexity in the organisation of building systems and components, one strategy includes reconstructing a system into different levels (i.e. a hierarchical network of building systems) through reconfiguring abstraction, the hiding of information, and interfaces. There are clearly-defined interfaces and buffers between levels and sub-building systems among networks, and by connecting and exploring the relationships between hierarchical networks, such as by mirroring the relationship between the hierarchical network of building components and the hierarchical network of design organisations, complexity can be reduced.

7.3.3 Alignment between multiple dimensions of modularity

7.3.3.1 Responding to the mirroring hypothesis: alignment between organisational and product dimensions

Mirroring hypothesis is the most typical discussion about the alignment relationships between multiple dimensions of modularity. The relationship between organisational structures and product structures (i.e. the 'mirroring' hypothesis) has been discussed for the past decade. For the AEC industry, project organisational structure is usually multi-organisational and formed by contractual relationships (Turner & Simister, 2001). It is concerned with establishing a temporary governance framework (Turner & Müller, 2003). A valuable assumption under this theory is that the building, as a one-off product (Katila et al., 2018), tends to 'mirror' its organisational structures in which they are developed. As the highest level of prefabrication, modular building assembly is more similar to the product assembly process than traditional on-site construction (Bertram et al., 2019). This highly integrated building type poses challenges to design and construction firms (Choi et al., 2019). Firms having not adapted their organisational structure to modular products limits their innovation and capability (Hall et al., 2020). Without adjustments in the organisational structure, the design process and products will fall into the 'mirroring trap' (Hall et al., 2020). There is a need for a more strategic modular solutions to transform project organisation for better building design.

This case study strongly validated and supported this assumption at the project level. As a modular healthcare building (i.e. a one-off modular product), Huoshenshan Hospital was affected by its modular organisation (see Table 20), and broke the 'mirroring trap' by adapting the temporary organisation to the one-off modular product (see Table 18). This radical innovation transformed the conventional DfMA path and integrated DfMA attributes (see Table 16). The sub-organisations were fully and effectively authorised internally to follow the building system rules and control requirements (see Table 20). This facilitated the independent operation of the organisation's sub-system modules at all levels, and formed a flexible organisational structure, which contributed to the realisation of concurrent design for manufacturing and assembly.

The Huoshenshan Hospital provided a live scenario for investigating the relationships between DfMA countermeasures to the pandemic. The challenges were manifold, including (1) risks and uncertainties due to more resource investment at the early stage; and (2) different interests and trust issues of stakeholders in the organisation network. Due to the rapid spread of COVID-19, the budget for Huoshenshan Hospital was not an obstacle - the government made a commitment regardless of cost. The design and construction firms were all state-owned enterprises, which meant that economic and market forces were less likely to impact construction activities. Political incentives from the government encouraged close collaboration and coordination between different project stakeholders. The common desire to help Wuhan urged all parties to unite and cooperate. All stakeholders shared the same goal and worked together. All employees wore masks to work in the office and on the construction site and used online meetings to communicate in real-time. The concept of DfMA was successfully implemented. Organisational integration occurred because the 'mirror' breaking process became possible.

In Huoshenshan Hospital, the coupling of modular organisation with the technical structure of the modular building provided the mechanism to integrate DfMA. Designers made design trade-off decisions together, and multiple disciplines were integrated. As a characteristic of modularity (Langlois, 2002), information hiding provided a foundation for concurrent design and construction. It divided knowledge and work interfaces to make independent work possible in a very complex system.

Various studies have explored design strategies to improve quality (Woo & O’Connor, 2021), standardisation in design (Choi et al., 2020a), participation and coordination (Jang et al., 2019), and modularisation (Choi et al., 2020b). This research contributes to the existing literature and knowledge base regarding DfMA guidelines by exploring integration and implementation. First, the common attributes behind various DfMA guidelines were revealed. In addition, the conflict and relative nature of DfMA attributes were recognised, and the importance of integrating DfMA attributes more than integrating DfMA guidelines individually was highlighted. Second, integrated approaches to DfMA were proposed by relating the theory of DfMA to systems integration. Integration could not be achieved without management strategies that corresponded to DfMA in terms of project organisation. Third, the knowledge base of DfMA research was added to from an organisational lens, and integrated approaches through the lens of the mirroring hypothesis were facilitated. The correlation between organisational structure and product structure in a modular building were explored regarding implementation of DfMA. Through aligning the modular organisations with modular buildings, multi-disciplines can be systematically integrated to facilitate building systems integration. The breaking process of the 'mirroring trap' brought opportunities to but also raised potential challenges for design and construction firms.

In summary, the mirroring hypothesis in the AEC industry was examined for the first time in the context of project levels in building design. The 'mirroring hypothesis' (one of the assumptions of modularity theory), has been tested in many industries, including the air conditioning industry (Cabigiosu & Camuffo, 2012), software industry (MacCormack et al., 2012), pensions industry (Burton & Galvin, 2022), whole-goods industry (Belkadi et al., 2018), information technology industry (Hao et al., 2017), electric vehicle industry (Chen et al., 2019), and the AEC industry (Hall et al., 2020).

The existence of the mirroring hypothesis in building projects in the AEC industry was strongly supported by this case study. Breaking the 'mirroring trap' through collaborative, concurrent engineering and an integrated organisational structure was critical to the modular, integrated approach to DfMA. By breaking the 'mirroring trap', effective integration of complex building systems in the DfMA occurred.

This research studied the construction of the first emergency building to combat COVID-19 (i.e. Huoshenshan Hospital) and proved that (1) the 'mirroring' of organisational structure to technical structure helped integrate DfMA attributes; (2) systems integration in a complex building relied more on integrated DfMA rather than the use of one or some of DfMA guidelines; and (3) integrated DfMA processes strengthened organisational adaptation (the 'mirror' process).

7.3.1.2 Responding to Fine's three-dimensional theory of modularity: alignment between product, process and supply chain dimensions

In addition to the analysis of product and organisational structure, the relationship between a product, process and supply chain was also analysed. Fine et al. (2005) claimed these three elements tend to reinforce each other and be aligned along the integrity-modularity spectrum. Fine's three-dimensional modularity theory claims modular products tend to be designed and built by both modular processes and a modular supply chain (Fine et al., 2005). Voordijk et al. (2006) revised Fine et al.'s (2005) three-dimensional modularity theory to analyse the relationship between these three elements and their impact on construction projects in the AEC industry. Voordijk et al. (2006) evaluated the applicability of Fine's three-dimensional modularity concept, and showed its capability in describing the degree of modularity of products, processes and supply chains. However Fine et al.'s three-dimensional concept needs to be further refined to make up for the current shortcomings of being used in the AEC industry (Voordijk et al., 2006).

Voordijk et al.'s (2006) definitions of process modularity and supply chain modularity in the AEC industry were developed in this research. Voordijk et al. (2006) identified process modularity as production and manufacturing techniques, such as OSC, and regarded organisational modularity as project delivery systems, such as design-build. Voordijk et al.'s (2006) definition of process modularity in the AEC industry only focused on the construction stage, and the definition of organisational modularity in the industry only focused on vertical relationships. These definitions do not allow for a comprehensive understanding of the supply chain, nor are they suited for an analysis of the design stage. Therefore, this research focused on the processes around the design phase as a context for the analysis of process modularity. In terms of the supply chain, not only vertical relationships were considered, but horizontal relationships were also integrated.

The results showed that standardisation of the supply chain provided the basis for fault tolerance and standardisation of design. Due to time constraints, Huoshenshan Hospital could only use materials and equipment that were in stock. As a single supplier could rarely supply all the needed materials and equipment, multiple suppliers were used, and different specifications had to be adopted. The differences in the specifications of goods posed a challenge to the standardised design. A strategy at the level of the product was implemented. For example different types of goods were grouped and arranged in zones, so goods within each zone could be relatively standardised, rather than trying to standardise the entire project. This strategy represented a response to the challenge of non-standardisation in the supply chain through the product modularity principle of more flexibility. This strategy also demonstrated that improving the supply chain shaped and improved product design. Suppliers with products with the same specifications corresponded to areas of use that were divided by specifications, indicating a correspondence between a modular supply chain and modular products. Differences in procedures for the design and construction of products with different specifications led to a corresponding partitioning and modularisation of the process.

The case study results showed that product modularity changed the traditional design process through the reconfiguration of abstraction, information hiding and interfaces. These three basic strategies promote the characteristics of process modularity, which are (1) process standardisation, (2) process resequencing, and (3) process postponement (Feitzinger & Lee, 1997). The transformation from the cast-in-situ concrete hospital structures to the hybrid modular hospital represents a process of modularisation of the physical product components. Subsequently, the allocation of design tasks was reconfigured, as new knowledge and information requirements brought in by emerging technologies could not be managed in conventional construction agencies with the traditional assignment of roles. If the traditional assignment of roles continues, subcontractors and designers will make changes, leading to a decrease in design quality and production efficiency.

In addition, the research distinguished the relationship between organisational modularity and supply chain modularity within the context of building design in the AEC industry. Some studies regard the occurrence of organisational modularity at the level of firms (Brusoni, 2005; Galunic & Eisenhardt, 2001; Quan, 2006), while other studies define organisational modularity at an inter-firm level (Sanchez & Mahoney, 1996). This co-existence and lack of clarity also appears in studies testing the mirroring hypothesis.

Supply chain modularity focuses on the division of labour within a supply chain network for specific functions and tasks, and how companies in the network interact with each other (Voordijk et al., 2006). Supply chain modularity is focused at the inter-firm level. In particular, in the AEC industry, the project is a temporary organisation involving multiple firms with temporary relationships established by contract. The confusion and overlap between key concepts can lead to a lack of rigor in theoretical exploration of modularity. With a focus on DfMA in the design phase, the internal relationships in the design organisation were categorised within organisational modularity, while inter-firm relationships between the design organisation and other organisations in the project were categorised within supply chain modularity. Based on this distinction, clear conceptual boundaries were established which enabled all organisational scenarios in a project to be categorised.

In general, the product, process and supply chain are interrelated. Building on the concept in the previous chapter on the mutual influence of product structure and organisational structure, a new four-dimensional modular relationship is proposed, in which the product design, process, organisation and supply chain influence each other. That is, a modular product can be shaped and driven by relationships between a modular process design, a modular organisational structure, and a modular supply chain. Integral products can be shaped and driven by integral process design, integral organisational structures, and integral supply chain relationships. Building systems integrators need to understand the relationships between these dimensions and how to use these relationships to improve design and achieve building systems integration.

7.3.4 Gap between alignment and reinforcement relationships

The alignment of multiple dimensions of modularity (see Figure 33) does not always benefit the design, and is not the only choice in all design situations. In architectural practices, different dimensions of modularity can be strongly independent. For example, a building project can adopt highly modular physical components while the design process or organisation still maintains low-level modularity. Conversely, it can also be possible that a building project incorporated modular processes within a cast-in-situ type construction. Therefore, building systems integration does not depend on a high degree of single modularity or all dimensions of modularity. A modular alignment of different dimensions does not confirm building systems integration.

(See Figure 33 on the next page)

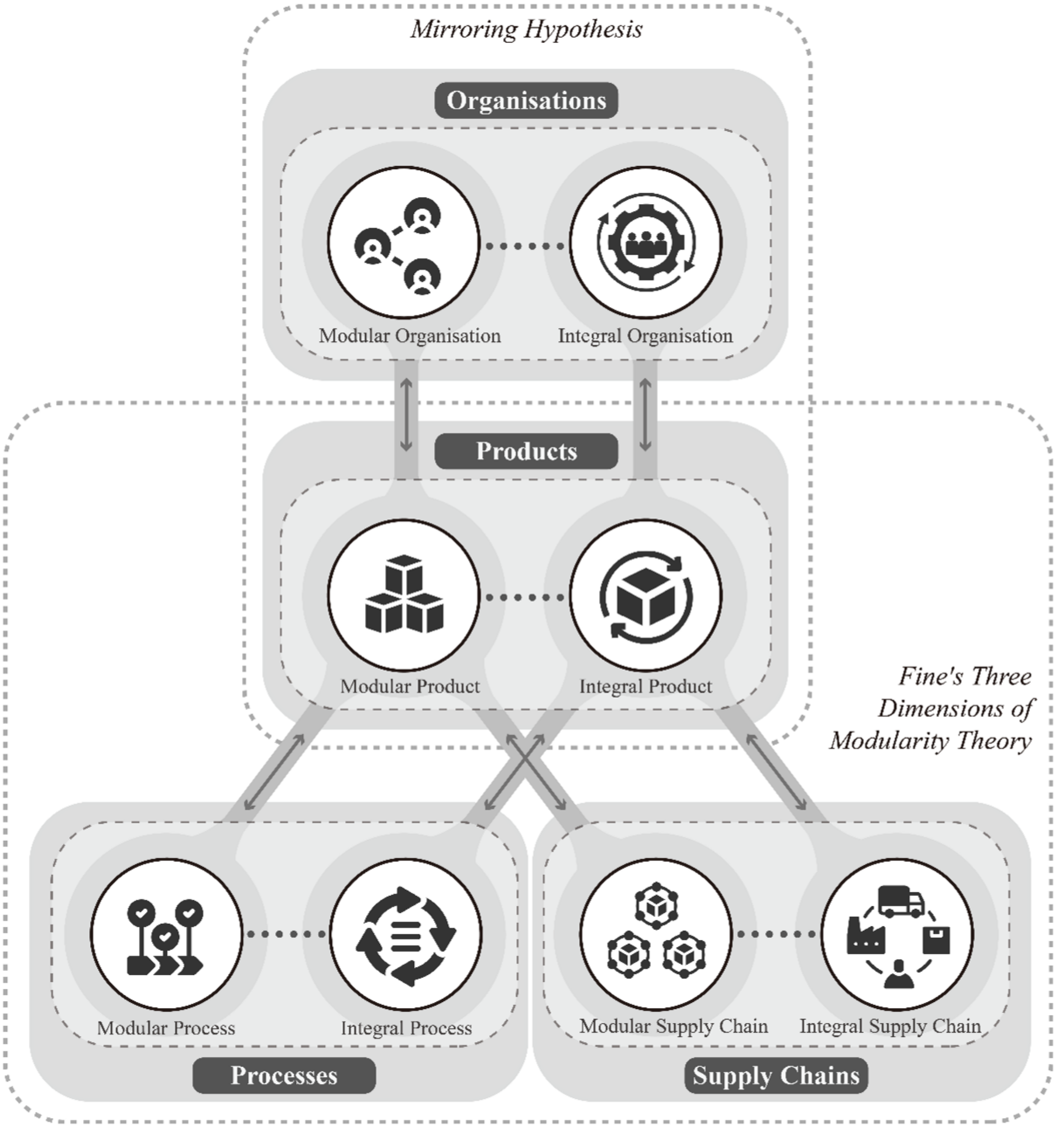


Figure 33 Alignment between multiple dimensions of modularity

Many previous studies describe the possible existence of an alignment relationship between two or three modular dimensions. Examples include studies that have explored the relationships between product and process modularity (Da Rocha & Kemmer, 2018), product and organisational modularity (Hall et al., 2020; Tee et al., 2019), product and supply chain modularity (Hofman et al., 2009; Pero et al., 2015), and product, process and supply chain modularity (Doran & Giannakis, 2011; Voordijk et al., 2006). However, none of these studies explain how to manifest alignment of the relationships or why it causes different outcomes. If alignment does not lead to building system integration, what relationships facilitate system integration? The answer is the reinforcement relationship

7.4 Reinforcement relationships between multiple dimensions of modularity

7.4.1 Modular alignment relationship

This research built upon previous research that identified the existence of the alignment relationships in architectural design, and provided new possibilities and insights into the choice of architectural design strategies by identifying the underlying mechanisms of the alignment relationships. Existing studies explored and tested the alignment relationships (Da Rocha & Kemmer, 2018; Gokpinar et al., 2010; Pero et al., 2010; Sosa et al., 2004; Tan et al., 2021; Voordijk et al., 2006), such as the relationship between integral product and integral process/organisation, and modular product and modular process/organisation. This case study built upon the previous research and focused on how, in the field of design, these alignments are achieved.

The examination of Huoshenshan Hospital case revealed two discernible alignment patterns. The first pattern identified is that a single strategy can act on multiple dimensions of modularity simultaneously, known as synchronised alignment, as evidenced in Figure 34. The second pattern identified is that different strategies can act on different dimensions of modularity, referred to as the asynchronous alignment, as shown in Figure 35. For example, see Table 22, in the alignment between process and organisational modularity, a typical strategy in the design process at Huoshenshan Hospital was concurrent processes for design and review. At the same time, the construction team had a corresponding engineer involved in the design process, and the design team had a designer involved at the construction site. This innovative approach to collaboration not only reshaped processes and drove modularity in the processes, but also reshaped the organisational relationships and modularity. Threats and challenges existed in both process and organisational modularity. But the alignment of strategies reduced complexity in the individual and aligned dimensions. Mutual reinforcement resulted directly from strategies derived from the modularisation process.

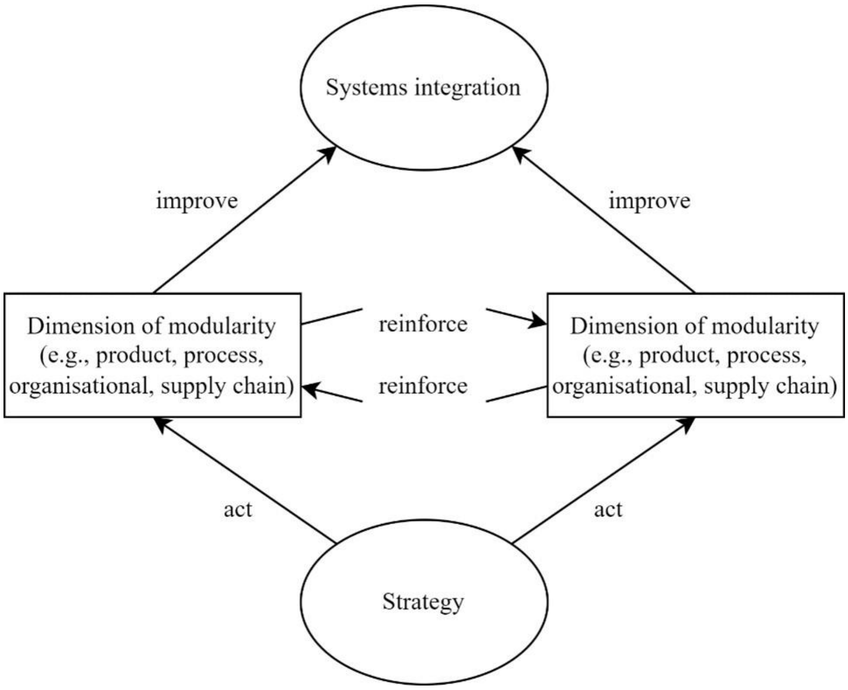


Figure 34 Modular alignment relationship through the same strategy (i.e. synchronised alignment)

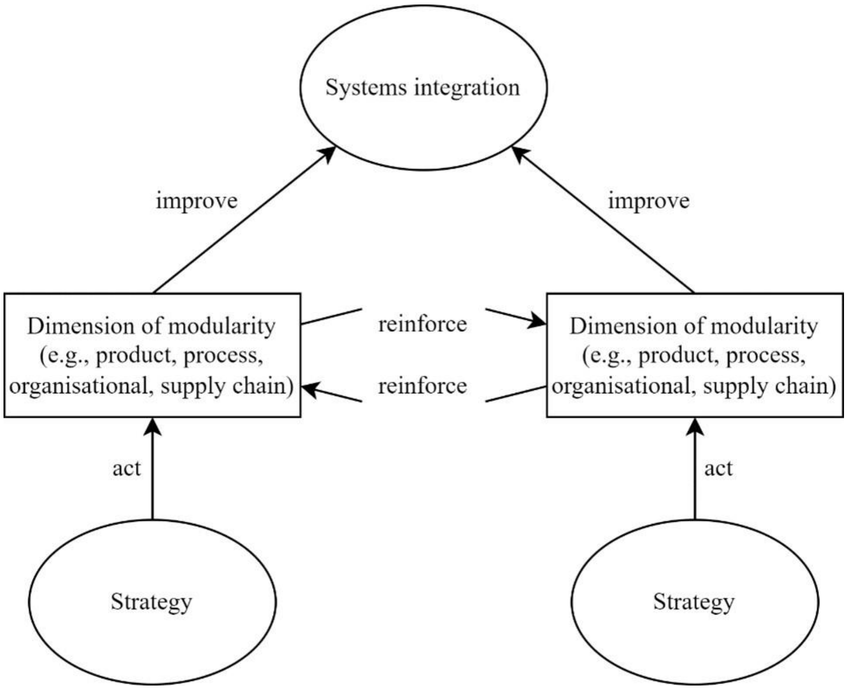


Figure 35 Modular alignment relationship through different strategies (i.e. asynchronous alignment)

Table 22 Examples of modular alignment relationships

Reinforcement relationships	Types	Examples
Alignment	Synchronised alignment	Organisational modularity: Different design disciplines all have designers from the main contractor (+responsibility proximity)
		Process modularity: Concurrent design process between interdisciplinary teams (+task proximity)
	Asynchronous alignment	Supply chain modularity: Collaborative alliance (+organisational proximity)
		Process modularity: Collaborative design process by involving purchasers/suppliers (+technological proximity)

Note: '+' means the increase of modularity level

In another type of alignment relationship, namely asynchronous alignment, different strategies acted at different dimensions of modularity, and reinforced each other. For example, in each of the seven building systems at Huoshenshan Hospital, designers applied the strategy of process modularity to achieve systems integration, which corresponded to the relationships in each supply chain system. The construction of each building system was achieved not only by the strategy of the designers, but through the coordination of the supply chain,. The modularity of the building system process corresponded to the modularity of the supply chain, but was achieved through different measures. The former relied on task management measures of the designer, while the latter relied on modularity achieved by strategies based on geography, organisation, and culture. Instead of aligning strategies during the modularisation process, different strategies were reinforced after the modularisation process.

7.4.2 Modular complement relationship

The possible drawbacks of modularity, such as the unwillingness or inability to cooperate due to internal specialisation (Tee et al., 2019), were confirmed in this case study, in that not all sub-systems of buildings were conducive to a reduction of complexity through modularity principles. Fundamentally, it is the critique of holism against reductionism, which argues that all parts of a system (e.g., the universe, the human body, etc.) are an organic whole and cannot be separated or understood separately. A compromise in the conflict between holism and reductionism is warranted. In contrast to existing work perceiving modular strategies and integral strategies as opposites, Tee et al. (2019) argue that they can be complementary for the collaboration at an inter-organisational level. In Huoshenshan Hospital case, the complexity that could not be reduced through modularity in one dimension (i.e. product modularity) was addressed by a modularity principle in another or multiple dimensions (i.e. process and organisational modularity). This type of multi-dimensional relationship of modularity is categorised as the modular complement relationship.

This type relationship is broadly divided into two categories. The first is one in which integration in a particular system is facilitated by sacrificing a certain level of modularity so that it has a lower level of modularity compared to other dimensions (i.e. subtraction complement, see Table 23 and Figure 36). The cost and risk of this reduced degree of modularity is addressed by modularity in other dimensions. For example, regarding product modularity, instead of using standardised interfaces, non-standardised interfaces for construction connectors were used to improve construction fault tolerance and resilience. The benefits of reduced modularity at the product modularity saved engineering time and reduced construction difficulty, and the use of non-standardised interfaces was superior to the use of standardised interfaces. The drawbacks due to the use of non-standardised interfaces were addressed through standardised measures in the process, organisational and supply chain dimensions.

The second is a relationship with one dimension that has a higher degree of modularity compared to other dimensions (i.e. addition complement, see Figure 37), thus making it more conducive to solving a particular problem. Again, the benefits of this non-alignment outweigh the negative effects, which allows the reinforcement between dimensions to be established. The modular complement relationship also confirms what some research has argued, that alignment between modular dimensions does not always exist. Instead, there are specific scenarios in which alignment needs to be broken to solve a very salient problem. Complexity may be solved by a modular complement relationship, which is an alternative approach that can reinforce relationships between multiple dimensions of modularity.

Table 23 Examples of modular complement relationships

Reinforcement relationships	Types	Examples
Complement	Addition complement	Product modularity: Same type of components/equipment used in one area (+component proximity)
		Process modularity: non-standardised process for non-standardised products (task proximity)
	Subtraction complement	Product modularity: non-standardised interfaces (-component proximity)
		Process modularity: Standardised/modularised design tasks (tasks proximity)
		Supply chain modularity: Local sourcing for equipment and building materials (geographic proximity)

Note: ‘+’ means the increase of modularity level; ‘-‘ means the decrease of modularity level

(See Figure 36 on the next page)

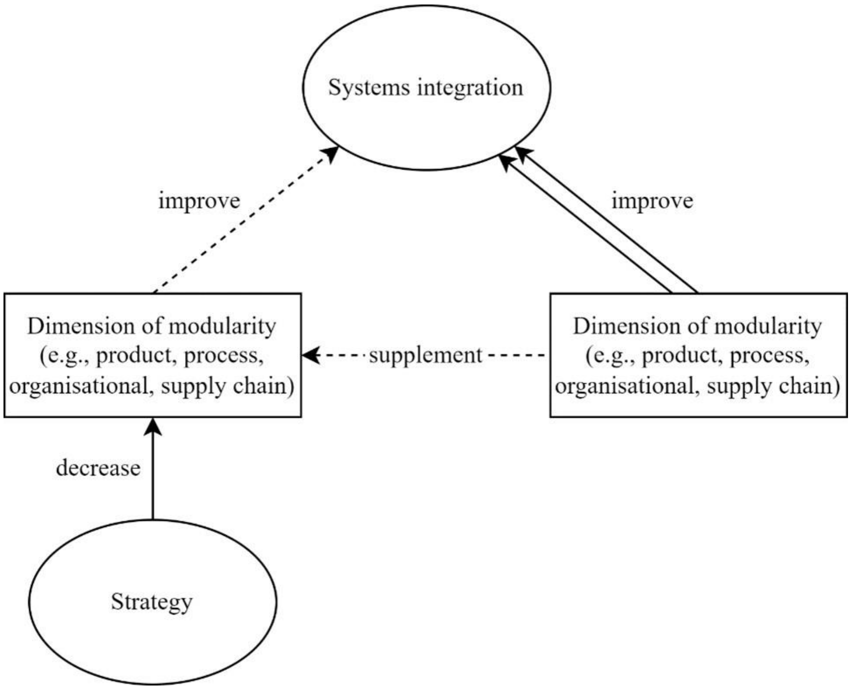


Figure 36 Modular complement relationship through the decrease of modularity (i.e. subtraction complement)

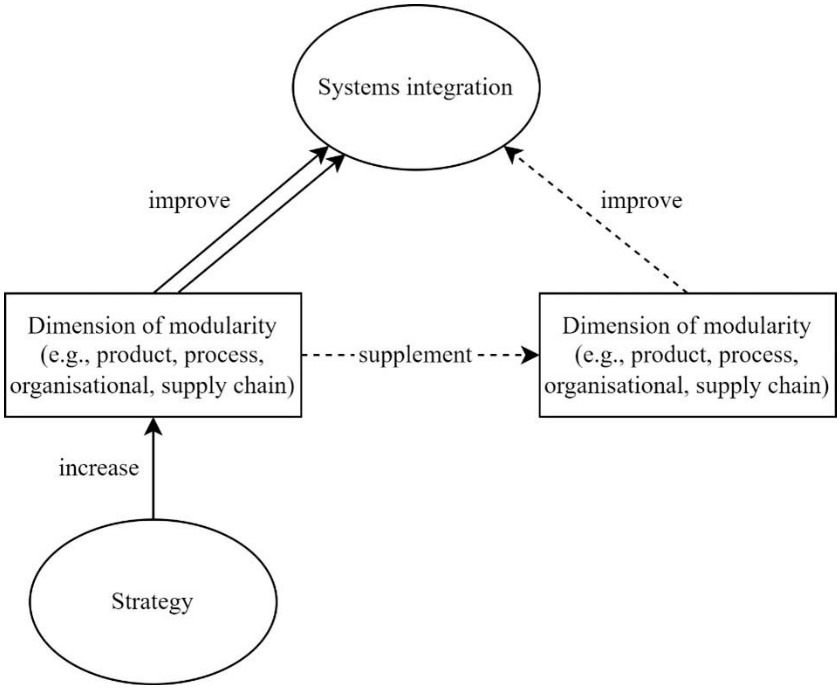


Figure 37 Modular complement relationship through the increase of modularity (i.e. addition complement)

7.4.3 Modular incentive relationship

In addition to the two relationships described above, there is a third relationship between multiple dimensions of modularity called the modular incentive relationship (see Figure 38). Incentivisation is one dimensions of modularity indirectly influences corresponding resources in another dimension, which creates a strategy of reinforcement, or matching of modularity. However, two modular dimensions can reinforce one another indirectly only when corresponding resources or matching strategies are available.

The use of digital technology, especially BIM, in the DfMA process illustrates a typical incentive-type of relationship. In the case of Huoshenshan Hospital, for example, the complex functions in the building necessitated many interfaces at the product modularity level for interaction between the various building system modules. To enhance product modularity, the relationship between building systems and interfaces needs to be collaborative. The many capabilities of BIM, such as collision detection can help solve technical problems that arise during product modularisation, especially with inter-disciplinary collaboration (Bhooshan, 2017; Wortmann & Tunçer, 2017).

BIM is not just a technical tool. In order to truly adapt to the use of BIM and embrace it, organisational changes are required. Thus, modularity can lead not only to the use of BIM in a project, but also to organisational change. Huoshenshan Hospital did not use BIM tools in the design process, due to the lack of appropriate resources (i.e., time) and matching strategies (i.e., strategies to cope with the lack of time). Thus, for the application of BIM tools, neither incentive, nor modular alignment, nor modular complement relationships are formed between product modularity and organisational modularity.

To illustrate an incentive relationship between product modularity and organisational modularity, the use of digital communication technology in the case study was an example. The organisation was motivated to adopt modularity due to the requirements of numerous building product information. For example, various WeChat groups were established for organising different teams. The hierarchy of information was transformed in the process. Abstraction, information hiding, and system interfaces between different sub-systems were implemented to different degrees in the case study. From the micro to the macro, hierarchical relationships between different architectural components, or dimensions, were developed differently. Compared to the modular alignment and the modular complement types of relationships, the modular incentive type of relationship was loosely-coupled and less direct, and its implementation was dependent upon corresponding resources and matching strategies. In general, the incentive relationship relied on an indirect reinforcement of modularity in another dimension through incentives.

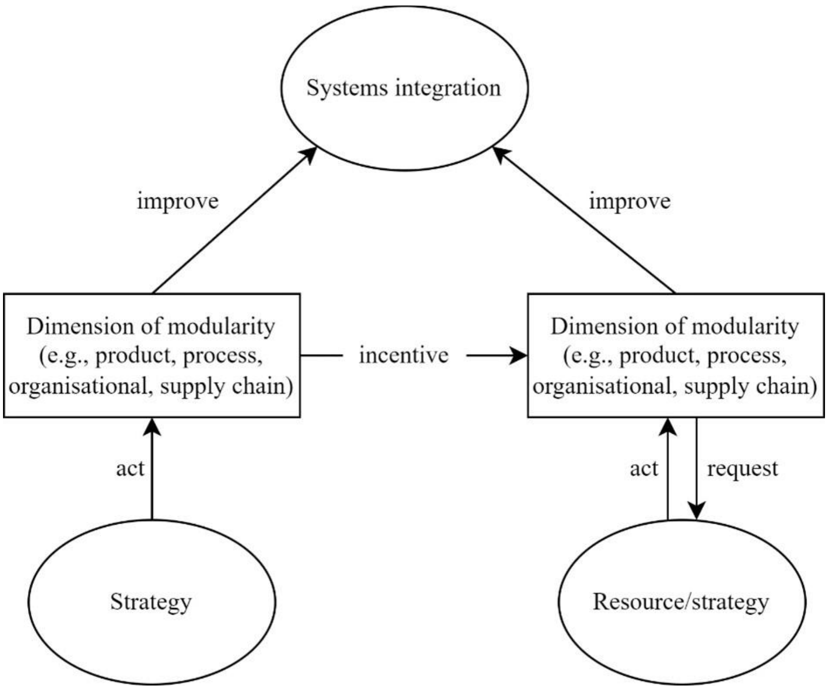


Figure 38 Modular incentive relationship

7.4.4 Capabilities of reinforcement relationships for DfMA

According to McComb and Jablokow (2022), deliberate consideration of multidisciplinary is imperative for the design community. Collaboration in design entails the involvement of multiple individuals and the coordination of design information and tasks. Therefore, team organisation is a pivotal aspect of design collaboration, given its potential to impact design communication and performance (Chiu, 2002). Consequently, communication, which encompasses the integration of specialised knowledge and the resolution of discrepancies among domain specialists, has emerged as an essential constituent of the design process (Sonnenwald, 1996). The capabilities of reinforcement relationships identified in this research have the potential to improve teamwork for integrated design activities.

This research identified how to use modularity as an integrated approach to impact and integrate various facets of design from. From a single modularity perspective, the reconfiguration of abstraction, information hiding, and interfaces is an essential strategy for modularising a traditional product, process, organisation or supply chain. This reconfiguration is necessary to adapt to the scenarios unique to modular hospital construction and the design tasks associated with these scenarios. However, the reconfiguration of abstraction, information hiding, and interface at all levels in all four dimensions is resource-intensive and challenging. In Huoshenshan Hospital, reconfiguration could not be implemented in all aspects of the four dimensions. For example, product modularity was not standardised at the interface level in all scenarios. When the relationships between modular alignment, modular complement, and modular incentive became tightly coupled and reinforced, they enhanced integrated design for the realisation of construction. The reinforcement relationship led to a better use of modularity which in turn reduced complexity, and was a strategy to manage design limitations and design process challenges.

7.5 Reflections and contributions

7.5.1 Advancement in theoretical understanding

This research is an exploratory investigation into the application of modularity to integrate DfMA in the construction industry, with a particular focus on healthcare construction in China using Huoshenshan Hospital as a case study. A central aspect of the research is understanding the relationships between different dimensions of modularity and how they can be leveraged to enhance DfMA. The study identified three reinforcement relationships. The research expanded upon the "mirroring hypothesis," which was previously validated at the construction-firm level by Hall et al. (2020). The mirroring hypothesis suggests an alignment between product modularity and organisational modularity. The study extends this by identifying the importance of alignment at the project level. Modular alignment can occur in a synchronised manner, with the same modularity principles acting on different dimensions, or asynchronously, with different principles acting on different dimensions.

Building on Tee's et al. (2019) work on complement relationships for integrated design, the study discussed how the complexity in one dimension can be compensated for by modularity principles in other dimensions. There are two types - subtraction complement, where the integration challenges of a system are facilitated by compromising a certain level of modularity; and addition complement, where a dimension with a higher degree of modularity is more conducive to solving a specific problem. Regarding modular incentive, it is an innovative finding where strategies in one dimension of modularity indirectly motivate the allocation of resources in another dimension, creating matched and reinforcing modularity strategies.

These reinforcement relationships are vital as they can reduce complexity and enable integration across organisation-process-product-supply-chain dimensions of digital-enabled DfMA. The research highlights that architects can take a leading role in integrating these dimensions, utilising modular alignment to adjust organisational structures and product design efficiently. In sum, this research significantly contributes to the existing knowledge by extending the mirroring hypothesis to the project level and identifying new modular relationships.

7.5.2 Practical reflections and contributions

From the perspective of digital-enabled DfMA, the case study provides practical insights and contributions for designers of both unique emergency modular and normal hospitals. Firstly, real-time design and iteration are made possible through digital-enabled approaches, allowing designers to make real-time modifications and adjustments during the construction process. This capability not only enhances design flexibility but also enables rapid response in emergency situations. Research reveals that this digital-enabled approach is not dependent on BIM software, indicating that designers can flexibly adopt information-sharing and optimisation methods based on project characteristics and situations. The construction process of Huoshenshan Hospital demonstrates how various traditional or non BIM-like digital-driven tools can be successfully integrated into the design and construction process. This provides designers with a demonstration of how to utilise these digital-enabled approaches effectively in practice.

Secondly, the successful construction of Huoshenshan Hospital heavily relied on efficient collaboration among the involved parties. This emphasises the importance of collaborative work and communication in implementing DfMA for designers. The driving force behind collaborative cooperation lies in consensus among the parties, with a common interest in the rapid completion of this emergency hospital project. This also suggests that practitioners need to consider how to establish and leverage the common interests of stakeholders as the foundation for cooperation. The construction of Huoshenshan Hospital utilised OSC and DfMA. Designers can learn from this project how to effectively utilise modular design to enhance construction efficiency. This research also contributes to the role of architects as integrators of building systems, promoting the mutual reinforcement relationship of multiple dimensions of modularity. The case of Huoshenshan Hospital provides designers with important insights on how to apply and optimise DfMA in practice, particularly in emergency situations. These experiences and lessons can offer valuable references for designers in future projects.

Furthermore, the advantages of digital-enabled DfMA can also be applied to normal hospital designs. Although Huoshenshan Hospital was an emergency construction, its considerations for flexibility are also applicable to the design of normal hospitals. For example, designers can consider how to design spaces that can adapt to technological changes and be easily retrofitted, as well as how to design buildings that can accommodate future demand changes. While normal hospitals may not require completion within a short timeframe like Huoshenshan Hospital, designers still need to consider how to achieve more efficient and flexible design while meeting building codes and standards. Therefore, this study provides many valuable insights and references for the design of normal hospitals as well.

7.5.3 Policy recommendations and impacts

This research's policy implications could extend to the broader adoption of DfMA in the construction field rather than only in the healthcare sector. This study could offer fresh insights for policies such as those being implemented by Singapore's Building and Construction Authority, which provides comprehensive guidelines for promoting DfMA in the construction industry, the strategic application steps advocated by the UK's Royal Institute of British Architects, and the educational and collaborative initiatives encouraged by Hong Kong's DfMA Alliance to promote OSC. Policymakers can encourage the adoption of OSC and digital-enabled DfMA not only by advancing education, financing, and regulation but also by taking into account the integration of processes, supply chains, and organisational designs.

This research conceives policies for promoting digital-enabled DfMA through the lens of socio-technical systems, taking into consideration the interaction and mechanisms between technology (e.g., products) and social aspects (e.g., processes, organisations, and supply chains). Concurrently, although the Huoshenshan Hospital project did not fully utilise BIM tools during its design phase, the focus on digital-enabled information integration and management was pivotal for enhancing design efficiency and saving time and resources. Policymakers should, therefore, encourage a more extensive emphasis on digital-enabled information optimisation in the construction industry, rather than solely focusing on the use of BIM software or modelling tools.

Specific for the healthcare sector, the mechanism of reinforcement relationships between multiple dimensions of modularity could be the basis and guidance for policymaking. The rapid construction of the Huoshenshan Hospital exemplifies the advantages of modularity and OSC in construction, especially during emergencies such as public health crises. Moreover, Huoshenshan Hospital’s construction entailed cross-sector collaboration and innovation involving various industries and professionals, including designers, engineers, construction workers, and medical personnel. This interdisciplinary collaboration offers a model for policymakers, highlighting the necessity of coordinated innovation across different domains in tackling complex and urgent challenges. Such coordination can include process and organisational innovations, such as the integration of design teams from both design and construction sectors. Furthermore, the Huoshenshan Hospital case demonstrates the criticality of swift response and construction of temporary facilities during emergencies.

In addition, policymakers can contemplate on integrating emergency preparedness into planning and policies, such as establishing disaster response plans or encouraging the creation of rapidly deployable modular facilities. Additionally, flexibility in construction standards and regulations is essential, as seen in the Huoshenshan Hospital case, where adjustments to conventional standards were indispensable for expeditious construction. Policymakers need to contemplate mechanisms that allow for greater adaptability in standards and regulations under certain emergency scenarios.

7.6 Chapter summary

This chapter presented the overall discussion. In conclusion, the research shows that reinforcing relationships between multiple dimensions of modularity is the underlying mechanism that allows for the integration of building systems. Architects can act as the building systems integrator by reinforcing modular alignment, modular complement and modular incentive relationships. Understanding the strengths and limitations of the four dimensions in a project leads to the optimisation of the configuration and structuring of 1) information channels; 2) information hierarchies; and 3) information scopes through the adoption of modularity, specifically the reconfiguration of abstraction, information hiding, and interfaces. As a result, strategic integration is achieved in digital-enabled DfMA. When multiple dimensions are coupled the delivery of building systems integration is possible.

This research builds upon the existing research on the alignment of relationships between multiple dimensions of modularity in the AEC industry. Categories within multiple dimensions of modularity were reidentified and reclassified. This research did not aim to establish one-for-all solutions or universal laws between the relationships of these dimensions, but rather to expand upon the existing established relationships, and understand the capabilities of the possible relationships between these dimensions.

Chapter 8 Conclusions

8.1 Introduction

This chapter presents the key findings of this research in relation to its research objectives. First, the chapter presents a summary of responses to the three guiding research questions. Next, the chapter highlights the academic contributions made by the research and also its implications for the industry. Finally, the concluding section explains the limitations and constraints faced while conducting this research, and introduces ideas for future research.

8.2 Summary of research insights

8.2.1 Conclusion 1 – Improving the digital-enabled DfMA relies on integrated approaches

Practitioners viewed the adoption of digital technologies like BIM software and DfMA strategies as nascent and not yet widespread in the industry at that time; and the implementation of improved digital-enabled DfMA relies on integrated approaches rather than the use of fragmented digital tools and DfMA guidelines.

Through an investigation of the case context present during the construction of the Huoshenshan Hospital, it was discerned that practitioners ubiquitously perceived that, within the ambit of industry practices at the time, the implementation strategies of digital technologies (such as BIM software) and DfMA guidelines were in a relatively nascent stage and had not yet achieved widespread adoption. Research also indicates that the complex challenges to implementation take two forms: the complexity of the strategies themselves, and the complexity of the collaboration required for implementing those strategies. Healthcare construction involves a variety of functions, corresponding knowledge/information, and a wide range of stakeholders; thus, it has unique characteristics that affect the way that BIM and DfMA are adopted. Standardisation in design is perceived as the most frequently employed

DfMA strategy. Practitioners in healthcare construction express concerns about the cost implications of BIM and DfMA, as they may result in increased costs instead of reducing them. It is important to note that BIM modelling software and DfMA design strategy are merely optional tools to achieve both initiatives and do not represent the purpose and realisation of BIM and DfMA. Rather, digital-enabled DfMA is the process for achieving building systems integration.

This research of Huoshenshan Hospital, the first emergency building to combat COVID-19, demonstrated that achieving systems integration in a complex building project necessitates the adoption of integrated approaches to DfMA, rather than the implementation of one or more DfMA guidelines. Partitioning of healthcare sub-systems, such as building function systems for corresponding design and construction, was conducive to the adoption of the most appropriate construction method strategies, either integral or modular strategies, in different sub-facilities, and enhanced the building systems integration. A modular integrated approach, therefore, is expected to be applicable to the integration of DfMA strategies in different functional facilities in the healthcare field, improving the overall popularity of industrialisation in the AEC industry.

8.2.2 Conclusion 2 – Modularity principles decrease DfMA complexity to building systems integration

Complexity hinders building systems integration in healthcare construction; modularity principles can reduce DfMA complexity to facilitate the realisation of building systems integration.

The construction of healthcare facilities is one of the most complex types of construction projects. Different building sub-systems need to be interwoven and interdependent in order to produce overall functionality. DfMA's contribution to the integration of building systems comes from two main directions, namely design strategy and design management strategy. The key to meeting the integration challenge lies in coordinating these strategies and compensating for their mutual shortcomings in the project context. The design strategy must therefore be based on the design management strategy, and the design management strategy needs to be fully informed by the design strategy. Building systems integration, therefore, is not only the result of the designer's integration of knowledge of individual systems, but also the result of a series of collaborative processes.

Modularity principles can be used to reduce the complexity of DfMA. By deconstructing a large system into different sub-systems, the reconfiguration of abstraction, information hiding and interfaces in different hierarchies of the system allows the modularisation strategy to be established. The strategy is further divided into four dimensions: product, process, organisation and supply chain. Starting with one or more of these dimensions can begin to address the complexity reduction challenges of a system or sub-system. These various attempts to apply modularity principles to reduce complexity in the design phase represent the essence of DfMA.

These applications also show that DfMA's focus on the performance of manufacture and assembly is no longer limited to design optimisation at the product-technical level, but can also be influenced by and carried out through different socio-technical perspectives (i.e. process, organisational and supply chain design) as an integrated practice of design. Manufacturability and assemblability thus become two dimensions with which to measure DfMA. The purpose of DfMA is to enable the building to form a physically and functionally integrated whole through design, i.e. through building systems integration. As a result, perceived measures for modularity principles in design have been categorised into four groups (across organisation-process-product-supply chain dimensions) through ten proximities, including function, component, task, technological, responsibility, knowledge, resource, geographic, organisational and cultural proximity, that impact the perception of four dimensions of modularity. These modularity principles help to decrease design complexity across these four dimensions, making building systems integration more attainable through DfMA.

8.2.3 Conclusion 3 – Reinforcement relationships can facilitate integrating building systems

Integrated approaches to digital-enabled DfMA rely on achieving reinforcement relationships between multiple dimensions of modularity, namely modular alignment, modular complement and modular incentive relationships, for building systems integration.

Reinforcement relationships between multiple dimensions of modularity, namely organisation-process-product-supply chain dimensions, is the underlying mechanism for integrating building systems. From a single modularity perspective, the reconfiguration of abstraction, information hiding, and the interface is an essential strategy for modularising a traditional product, process, organisation or supply chain. Reconfiguration allows for new scenarios that occur in modular hospital construction, and the new design tasks associated with these scenarios, to be adapted. However, reconfiguration under all of the four dimensions is resource-intensive and challenging.

DfMA may not be achieved if it is based on the realisation of single-dimensional modularity; matching multi-dimensional modularity is more likely to lead to success in DfMA. Each project has a unique product design, process design, organisational design and supply chain design. It is not just the conceptual ideas of the product design that lead to the final building; the final building is an integration of these four dimensions. This research argues that architects can take the lead in integrating all four dimensions during the design process and act as building systems integrators by utilising three relationships: modular alignment, modular complement and modular incentive relationships.

By understanding the strengths and limitations of the current state of the four dimensions, projects can optimise the configuration and structuring of 1) information channels; 2) information hierarchies; and 3) information scopes. This is achieved by adopting the basic strategy of modularity (the reconfiguration of abstraction, information hiding and interface). As a result, digital-enabled DfMA achieves strategic integration in this multi-dimensional coupled state, facilitating the delivery of building systems integration.

8.3 Research achievements and knowledge contributions

To address the research questions, this research investigated the implementation of BIM and DfMA in Huoshenshan Hospital to explore modularity principles, which revealed the multi-dimensional modularity and shed light on integrated approaches to digital-enabled DfMA for building systems integration in healthcare construction. Table 24 summarises the achievement of research objectives. This research explored current practices and strategies of digital-enabled approaches (i.e. BIM) and DfMA in in Huoshenshan Hospital, identified underlying modularity principles, and finally, described integrated approaches that facilitate the implementation of digital-enabled DfMA. This research shows that the reinforcement relationships between multiple dimensions of modularity, namely organisation-process-product-supply chain dimensions, is the underlying mechanism for impacting and integrating building systems. There are three relationships between these four dimensions of modularity that reinforce each other and facilitate digital-enabled DfMA, namely modular alignment, modular complement and modular incentive relationships. Digital-enabled DfMA achieves strategic integration in this multi-dimensional coupled state, facilitating the delivery of building systems integration.

(See Table 24 on the next page)

Table 24 Achievement of the research objectives and knowledge contributions

Research objectives	Summary of achievement
Objective 1: To reveal the context of the single case, namely perceived practices and strategies from practitioners for the use of digital-enabled approaches (i.e. BIM) and DfMA in China's healthcare construction industry;	This research employed a literature review, surveys and following-up interviews to address the knowledge contribution to the challenges of digital-enabled DfMA. The literature review analysed DfMA and BIM. An extensive questionnaire was then employed resulting in 183 valid responses to gauge the responses of China's healthcare construction participants. Follow-up interviews were subsequently conducted to verify some of the possible insights. The analysis identified 36 design challenges in 12 facets, and 12 digital adoption challenges in 4 facets. Overall, the research revealed that both digital-enabled approaches (i.e. BIM) and DfMA are in the early stages of healthcare construction applications in China and lag behind other building types. In particular, despite acknowledging that digitalisation and industrialisation will likely become the norm in future construction, many practitioners criticise the industry's efforts to engage in OSC and BIM practices. Rather than facilitating project design and construction, many practitioners believe that OSC and BIM negatively affect projects and merely satisfy customer or policy requirements.
Objective 2: To explore the implementation of digital-enabled approaches (i.e. BIM) and DfMA in Huoshenshan Hospital, and revealing their underlying modularity principles in product, process, organisation and supply chain;	A case study of Huoshenshan Hospital was used to explore the objectives of the research based on abductive reasoning. Data collection methods included a workshop, 18 interviews (covering design leaders and participants from all design disciplines, representing approximately one-third of the total project designers), and subsequent archival analysis. The case study analysis focused on BIM in terms of modelling tools and the use of information and communication tools for BIM, followed by an analysis of BIM in terms of process innovation. For DfMA, the research categorised 17 major DfMA strategies into five attributes. The case study identified ten proximities that impact the perception of four dimensions of modularity, through 28 perceived measures. It was found that the use of BIM modelling software was not present in the design process, which is consistent with common industry contexts observed under Objective 1. However, in terms of information and communications technology and the innovation process behind building systems integration, the case study is unique in the way information is managed, not in the adoption of the tool. The information management methods in this case represent a range of strategies in modular thinking. By understanding the strengths and limitations of the modularity strategy and

	adopting the basic strategy of modularity, namely the reconfiguration of abstraction, information hiding, and interface, the case project optimises the configuration and structuring of 1) information channels, 2) information hierarchies, and 3) information scopes. In terms of DfMA, the research deconstructs the various modularity strategies that underly the perceived measures of DfMA from each of the multi-dimensional modularity: organisation-process-product-supply chain dimensions (see Table 18, Table 19, Table 20 and Table 21).
Objective 3: To explore integrated approaches to facilitate the implementation of digital-enabled DfMA in Huoshenshan Hospital, and unpacking different types of reinforcement relationships and how they work in digital-enabled DfMA.	For the knowledge contribution to integrated approaches for digital-enabled DfMA, the research identified three reinforcement relationships of the perceived measures across four dimensions to integrate modular approaches to facilitate digital-enabled DfMA. For the three reinforcement relationships, the research first built on the knowledge of alignment relationships (i.e. mirroring hypothesis) and extends beyond Hall et al.'s (2020) construction-firm-level validation to identify the alignment relationship between product modularity and organisational modularity (i.e. mirroring hypothesis) at the project level to facilitate digital-enabled DfMA. Second, the research extended Tee et al.'s (2019) complement relationships for integrated design in projects through other dimensions of modularity to integrate modular approaches. Third, the research identified novel modular incentive relationships. The incentivisation strategies for one modularity dimension indirectly motivate corresponding resources for another dimension, thereby creating a matching/reinforcing modularity strategy. This research found that all three reinforcement relationships that exist in organisation-process-product-supply-chain dimensions can be used to facilitate integrated approaches for digital-enabled DfMA, and that there are two key characteristics of these reinforcement relationships. First, they can reduce the complexity of digital-enabled DfMA, namely the organisation-process-product-supply-chain dimensions. Second, they can be used to integrate various digital-enabled DfMA strategies, eliminating the fragmented use of digital tools and DfMA guidelines. Based on these findings, it is argued that architects can take the lead in integrating all four dimensions during the design process and utilise the three relationships for integrated approaches to DfMA. As a result, integrated approaches achieve digital-enabled DfMA in the multi-dimensional coupled state of four dimensions, thereby facilitating building systems integration.

8.4 Research implications

8.4.1 Theoretical implications on DfMA

The current study lays the foundation and bridge for the theoretical exploration of DfMA with modularity as the pathway. It investigates integrated approaches to digital-enabled DfMA—that improve building systems integration and thus develops a unique contribution to understanding DfMA. The research indicated the theoretical implications of how we know DfMA. In particular, it advanced new insights for understanding perceived DfMA strategies. Traditionally, most of the DfMA strategies mentioned in the literature are manufacturing-oriented; in contrast, this research developed and identified construction-oriented DfMA guidelines, and as a result, the implementation of these guidelines offers a simple and direct route for extending our perception of DfMA. This research provided insight into these perceived measures in terms of five design attributes and argued that the key to understanding DfMA is discerning how the conflicts between these attributes can be reconciled and integrated. Theoretically, this research shifts the focus from DfMA guidelines to the coordination and integration of DfMA attributes.

The research drew out the theoretical implications of how to implement DfMA. Reinforcement relationships, including modular alignment, complement and incentive relationships, are observed and encouraged in this study to facilitate integrated approaches to digital-enabled DfMA. The results of the analysis of the implementation showed that using some DfMA guidelines or BIM tools alone may not improve building systems integration through an entire life cycle. The integration of various DfMA guidelines is the most impactful for building systems integration. There are two key characteristics of these three reinforcement relationships. First, they can reduce the complexity of digital-enabled DfMA, namely the organisation-process-product-supply-chain dimensions. Second, they can be used to integrate various digital-enabled DfMA strategies, eliminating the fragmented use of digital tools and DfMA guidelines. Integrated approaches achieve digital-enabled DfMA in the multi-dimensional coupled state of four dimensions, thereby facilitating building systems integration.

8.4.2 Practical implications for DfMA

Practical implications are concerned with the direct impact of the findings on related practices or relevant parties. According to this research, DfMA has practical implications for two groups: design organisations and design practitioners. In general, this research provided a roadmap for the implementation of integrated approaches to DfMA. The findings enrich the understanding and application of modularity theory in design practice and thus enhance the ability of both organisations and practitioners to manage and simplify complex engineering design problems.

Regarding design organisations, this analysis used a single case study approach and the researchers collaborated intensively with the institution that generated the case to continuously collect data and improve its reliability. As a result, this research provides evidence-based conclusions about the implications of integrated design engineering for design organisations engaged in healthcare construction and, more broadly, in the construction of complex building types: the industry needs to focus on the innovation and integration of digital design processes and the integration of DfMA strategies, not just the implementation of BIM tools and DfMA strategies; reduce the difficulty of design in complex engineering systems by deconstructing complex systems and reconfiguring abstraction, information hiding and interfaces; promote optimal configuration of design capabilities by reinforcement of the four dimensions of product, process, organisation and supply chain; and invoke multi-dimensional design strategies to enhance building systems integration. The results of the case study indicated that reducing complexity was essential to achieving integration in engineering projects, and in general, this research provided both a theoretical lens and a new approach for design organisations to reach this goal.

By presenting Wuhan's experience, this research can also enlighten design practitioners by encouraging them to use various DfMA strategies to rapidly achieve improved healthcare construction capabilities, and to coordinate and resolve conflicts between various DfMA attributes. In addition to reducing the complexity of building systems integration through design strategies, the research will hopefully inspire design practitioners to become building systems integrators through the proposed strategies for design processes, organisational design and supply chain management. Also, the research facilitated the proper understanding and use of BIM by practitioners to enable DfMA and provided new pathways for design practitioners to evaluate the extent to which digital-enabled DfMA is implemented. This research pointed out the way to modular building design, and design practitioners can adopt the integrated approaches as a new approach to planning healthcare facilities. Finally, the research also clarified the mission and role of the building systems integrator in digital-enabled DfMA. The results of the case study suggested that the core competence of the integrator lay in the ability to reconstruct complex building systems by means of modularity, thus providing the basis for the integration of the various design disciplines.

In general, the AEC industry needs to focus on 1) the innovation and integration of digital design processes and the integration of DfMA strategies in addition to the implementation of BIM tools and DfMA strategies; 2) reducing the difficulty of design in complex building systems by deconstructing, reconfiguring, and integrating building systems; and 3) promoting design capabilities by optimising reinforcement relationships of the multi-dimensional modularity to enhance building systems integration. The case study results demonstrate that reducing complexity can help design organisations to comprehensively integrate engineering design. By analysing the situation in Wuhan, this research can enable relevant practitioners to utilise the developed design approaches to achieve rapid healthcare construction capabilities. Furthermore, examining an extreme situation can provide a wide range of strategic solutions for standard major healthcare construction, including product, process, organisation, and supply chain design.

8.5 Research limitations

This research drew upon qualitative data to conduct a single case study in the context of COVID-19 in China, which was a very unique situation and different from the setting for most major general healthcare construction projects. As a result, the research might have limitations for the generalisation of the results in terms of case number and case selection.

First, regarding the case number, the limitation of a single case study is that it is appropriate for a question starting with ‘how’ and ‘why’, but hard for a question starting with ‘what’. Therefore, the findings do not represent comprehensive and widely generalisable conclusions for DfMA guidelines and measures; there may be appropriate guidelines and measures that are outside of the scope of this research. As for the discussion of the multi-dimensional modularity, it was difficult to generate a strong correlation or causal relationship between the four dimensions within a single case study. In addition, this research did not assume that the three reinforcement relationships that were discovered exist in all practices, nor does it mean that only these three relationships exist. There may be other types of reinforcement relationships outside the three observed types that can also be identified as components of integrated approaches in the future. The findings are considered internally verified and thus consistent within the context of this specific case, but there is further research needed to externally test these propositions – in other geographies, at other times, and possibly in other contexts.

Second, regarding case selection, the complexity of Huoshenshan Hospital, the first hospital to be built globally in direct response to the COVID-19 emergency, may be different from that of other major hospitals. For example, the construction of major hospitals often lasts for several years and generally experiences issues such as changes in the core team, equipment updates, and policy changes that affect the engineering design. Huoshenshan Hospital, however, was designed and built in just ten days, which dramatically reduced such issues. In addition, the institutional context in which the case study took place also affected the potential for the generalisation of the findings. Regional governments are often responsible for healthcare construction in China, and they have a strong orientation towards benefiting society, so the design was constrained by the culture, policies and economic level of a region. Such differentiation may affect the ability to generalise from the conclusions. Furthermore, the unique nature of the case emphasizes the importance of conducting further research to externally test the propositions derived from this case study in other geographies, at different times, and in different contexts.

8.6 Future research and directions

8.6.1 Future research to address possible research limitations

Future research can address these possible methodological limitations. First, future studies may focus on adapting to changes in different phases of a long-term megaproject (i.e. the construction of major hospitals) in China to integrate DfMA and promote building systems integration. By examining more typical and representative cases in the healthcare construction industry, implications with wider generalisability can be understood. Second, as noted above, the construction of healthcare facilities is often funded and driven by regional governments and thus possesses very particular regional characteristics; as a result, healthcare construction varies significantly from country to country. Future case studies could focus on healthcare construction by considering different geographies, times, and potentially different contexts to explore the validity of research findings through comparative analysis.

8.6.2 Directions for advancing DfMA studies

In addition to remedying the limitations of this research, future work could build on this research and continue to advance DfMA in multiple directions. First, future research should further develop integrated approaches in two main sub-directions. In the first sub-direction, researchers could focus on the manifestations, strategies, problems and challenges of the single modularity dimension in the DfMA process. As digitalisation progresses, many new perspectives on modularity that help the understanding of the construction project process are beginning to emerge, such as service modularity. Research in these areas is still missing in the DfMA field. In the second sub-direction, future research could continue to advance the research of reinforcement relationships. The clarification of these relationships is conducive to the realisation of modularity in DfMA. In addition, future work could use quantitative research to identify the impacts and relationships of the multi-dimensional modularity.

Second, future research can further incorporate digital-enabled approaches (i.e. BIM) into the research of DfMA. The digital-enabled DfMA in this research represented a modular integrated approach in the daily practice of China's BIM implementation, but the case selection did not represent state-of-the-art practices in terms of the use of digital tools. As new technologies emerge, such as digital twins, blockchain and artificial intelligence, approaches to DfMA implementation will change dramatically; however, the combination of these emerging technologies and DfMA has not yet been fully examined. Therefore, if digital-enabled DfMA is to be fully understood and implemented, future research should focus more on these techniques. The adoption and implementation of these technologies will also pose formidable challenges for design organisations and design practitioners. How to adapt the reinforcement relationships between multiple dimensions of modularity and thus reduce the complexity for the implementation and inclusion of new technologies into the design process is a vital question for future study.

8.7 Closing remarks

The COVID-19 pandemic catalysed digitalisation, industrialisation and healthcare construction. While the essential principles of BIM and DfMA are often mentioned in healthcare construction, it is the design and process for building systems integration that represents the core rationale for adopting digital-enabled DfMA. The innovative contribution of this research lies in the mechanism of building systems integration based on integrated approaches through the reinforcement of multi-dimensional modularity in the design phase to understand and implement digital-enabled DfMA. Healthcare construction is a highly complex and dynamic engineering system. Building systems integrators in design organisations, often architects, are faced with design challenges from a variety of stakeholder requirements. Integrated design based on modularity theory leads to innovative approaches that invoke strategies to reconstruct complex systems and reduce engineering complexity. For design organisations, reduction of complexity is a core practice for solving complex engineering and design challenges; the presence of digital-enabled approaches relies on and consolidates this core competence in integrated design.

References

Aalto, L., Sirola, P., Kalliomäki-Levanto, T., Lahtinen, M., Ruohomäki, V., Salonen, H., & Reijula, K. (2019). User-centric work environments in modular healthcare facilities. *Engineering, construction and architectural management*.

Aapaoja, A., & Haapasalo, H. (2014). The challenges of standardization of products and processes in construction. Proceedings of the 22nd Annual Conference of the International Group for Lean,

Abanda, F., Tah, J., & Cheung, F. (2017). BIM in off-site manufacturing for buildings. *Journal of Building Engineering*, *14*, 89-102.

Abdelhameed, W. A., & Saputra, W. (2020). Integration of building service systems in architectural design. *J. Inf. Technol. Constr.*, *25*, 109-122.

Abdul Nabi, M., & El-adaway, I. H. (2020). Modular construction: Determining decision-making factors and future research needs. *Journal of management in engineering*, *36*(6), 04020085.

Adebayo, A. K., Price, A., & Gibb, A. (2006, 4-6 September 2006). Impact of modern methods of construction on healthcare infrastructure. Proceedings 22nd Annual ARCOM Conference, Birmingham, UK.

Ajayi, S. O., Oyedele, L. O., Akinade, O. O., Bilal, M., Alaka, H. A., Owolabi, H. A., Kadiri, K. O. J. R., & Reviews, S. E. (2017). Attributes of design for construction waste minimization: A case study of waste-to-energy project. *73*, 1333-1341.

Akanni, P., Oke, A., & Akpomiemie, O. (2015). Impact of environmental factors on building project performance in Delta State, Nigeria. *HBRC Journal*, *11*(1), 91-97.

Alharahsheh, H. H., & Pius, A. (2020). A review of key paradigms: Positivism VS interpretivism. *Global Academic Journal of Humanities and Social Sciences*, *2*(3), 39-43.

Archer, M., Bhaskar, R., Collier, A., Lawson, T., & Norrie, A. (2013). *Critical realism: Essential readings*. Routledge.

Architects, R. I. o. B. (2021). DfMA Overlay to the RIBA Plan of Work. In: RIBA London, UK.

Arif, M., & Egbu, C. (2010). Making a case for offsite construction in China. *Engineering, construction and architectural management*.

Arif, M., Goulding, J., & Rahimian, F. P. (2012). Promoting off-site construction: Future challenges and opportunities. *Journal of architectural engineering*, *18*(2), 75-78.

Arkin, H., & Paciuk, M. (1997). Evaluating intelligent buildings according to level of service systems integration. *Automation in Construction*, *6*(5-6), 471-479.

Ashley, S. (1995). Cutting costs and time with DFMA. *Mechanical Engineering*, *117*(3), 74-77.

Austin, S. A., Thorpe, A., Root, D., Thomson, D., & Hammond, J. (2007). Integrated collaborative design. *Journal of Engineering, Design and Technology*.

Azzi, A., Battini, D., Faccio, M., & Persona, A. (2011). Variability‐oriented assembly system design: a case study in the construction industry. *Assembly automation*.

Bachman, L. R. (2004). *Integrated buildings: The systems basis of architecture* (Vol. 9). John Wiley & Sons.

Baldauf, J. P., Formoso, C. T., & Tzortzopoulos, P. (2021). Method for managing requirements in healthcare projects using building information modelling. *Engineering, construction and architectural management*.

Baldwin, C. Y., & Clark, K. B. (2002). The option value of modularity in design. *Harvard NOM Research Paper*, *1*, 1-14.

Baldwin, C. Y., & Clark, K. B. (2006). Modularity in the design of complex engineering systems. In *Complex engineered systems* (pp. 175-205). Springer.

Baldwin, C. Y., Clark, K. B., & Clark, K. B. (2000). *Design rules: The power of modularity* (Vol. 1). MIT press.

Baldwin, C. Y., & Henkel, J. (2015). Modularity and intellectual property protection. *Strategic management journal*, *36*(11), 1637-1655.

Ballard, G., & Howell, G. (1998). What kind of production is construction. Proc. 6 th Annual Conf. Int'l. Group for Lean Construction,

Baloi, D., & Price, A. D. (2003). Modelling global risk factors affecting construction cost performance. *International journal of project management*, *21*(4), 261-269.

Banks, C., Kotecha, R., Curtis, J., Dee, C., Pitt, N., & Papworth, R. (2018). Enhancing high-rise residential construction through design for manufacture and assembly–a UK case study. *Proceedings of the Institution of Civil Engineers-Management, Procurement and Law*, *171*(4), 164-175.

Bao, Z., Laovisutthichai, V., Tan, T., Wang, Q., & Lu, W. (2022). Design for manufacture and assembly (DfMA) enablers for offsite interior design and construction. *Building Research & Information*, *50*(3), 325-338.

Başarır, B., & Altun, C. M. (2018). A redesign procedure to manufacture adaptive façades with standard products. *Journal of Facade Design and Engineering*, *6*(3), 77-100.

Batty, M. (2009). Generating cities from the bottom up: Using complexity theory for effective design. In *Embracing Complexity in Design* (pp. 17-34). Routledge.

Bazeley, P. (2013). *Qualitative data analysis: Practical strategies*. sage.

BCA. (2016). *BIM for DfMA Essential Guide*. B. a. C. Authority.

Beatty, B. (2018). Streamlined construction: Seven steps to offsite and modular building. *London: Balfour Beatty*.

Belkadi, F., Vlachou, E., Kumar-Gupta, R., Zogopoulos, V., Kaya, M., Bernard, A., Mourtzis, D., Natalizio, S., Büyükdığan, B. G., & Tekin Bayrak, I. (2018). Modularity as a support for frugal product and supplier network co-definition under regional market constraints: a mirroring hypothesis application. *International Journal of Production Research*, *56*(20), 6575-6590.

Benassi, M. (2009). Investigating modular organizations. *Journal of Management & Governance*, *13*(3), 163-192.

Berard, E. V., & Twain, M. (1993). Abstraction, encapsulation, and information hiding. *E Berard Essays on Object-Oriented Software Engineering*, *1*.

Bertram, N., Fuchs, S., Mischke, J., Palter, R., Strube, G., & Woetzel, J. (2019). Modular construction: From projects to products. *McKinsey & Company: Capital Projects & Infrastructure*, 1-34.

Bhooshan, S. (2017). Parametric design thinking: A case-study of practice-embedded architectural research. *Design studies*, *52*, 115-143.

Bhosekar, A., Badejo, O., & Ierapetritou, M. (2021). Modular supply chain optimization considering demand uncertainty to manage risk. *AIChE Journal*, *67*(11), e17367.

Bishop, R. C. (2007). The philosophy of the social sciences: An introduction.

Bogue, R. (2012). Design for manufacture and assembly: background, capabilities and applications. *Assembly automation*.

Booch, G. (1990). *Object oriented design with applications*. Benjamin-Cummings Publishing Co., Inc.

Boothroyd, G. (2005). *Assembly automation and product design*. crc press.

Boyce, C., & Neale, P. (2006). Conducting in-depth interviews: A guide for designing and conducting in-depth interviews for evaluation input.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative research in psychology*, *3*(2), 77-101.

Bridgewater, C. (1993). Principles of design for automation applied to construction tasks. *Automation in Construction*, *2*(1), 57-64.

Brusoni, S. (2005). The limits to specialization: problem solving and coordination in 'modular networks'. *Organization studies*, *26*(12), 1885-1907.

Brusoni, S., & Prencipe, A. (2001). Unpacking the black box of modularity: technologies, products and organizations. *Industrial and Corporate Change*, *10*(1), 179-205.

Burpee, H. (2008). History of healthcare architecture. *Integrated design lab Puget sound*, 1-3.

Burton, N., & Galvin, P. (2022). Modularity, value and exceptions to the mirroring hypothesis. *Journal of Business Research*, *151*, 635-650.

Cabigiosu, A., & Camuffo, A. (2012). Beyond the "mirroring" hypothesis: Product modularity and interorganizational relations in the air conditioning industry. *Organization Science*, *23*(3), 686-703.

Caixeta, M. C. B. F., & Fabricio, M. M. (2021). Physical-digital model for co-design in healthcare buildings. *Journal of Building Engineering*, *34*, 101900.

Camacho, D. D., Clayton, P., O'Brien, W. J., Seepersad, C., Juenger, M., Ferron, R., & Salamone, S. (2018). Applications of additive manufacturing in the construction industry–A forward-looking review. *Automation in Construction*, *89*, 110-119.

Campagnolo, D., & Camuffo, A. (2010). The concept of modularity in management studies: a literature review. *International Journal of Management Reviews*, *12*(3), 259-283.

Chang, Y.-F., & Shih, S.-G. (2013). BIM-based computer-aided architectural design. *Computer-Aided Design and Applications*, *10*(1), 97-109.

Chauhan, K., Peltokorpi, A., Lavikka, R., & Seppänen, O. (2022). The Monetary and Non-Monetary Impacts of Prefabrication on Construction: The Effects of Product Modularity. *Buildings*, *12*(4), 459.

Chen, C., & Tang, L. (2019). BIM-based integrated management workflow design for schedule and cost planning of building fabric maintenance. *Automation in Construction*, *107*, 102944.

Chen, K., & Lu, W. (2018). Design for manufacture and assembly oriented design approach to a curtain wall system: A case study of a commercial building in Wuhan, China. *Sustainability*, *10*(7), 2211.

Chen, K., Lu, W., Peng, Y., Rowlinson, S., & Huang, G. Q. (2015). Bridging BIM and building: From a literature review to an integrated conceptual framework. *International journal of project management*, *33*(6), 1405-1416.

Chen, K., Xu, G., Xue, F., Zhong, R. Y., Liu, D., & Lu, W. (2018). A physical internet-enabled building information modelling system for prefabricated construction. *International Journal of Computer Integrated Manufacturing*, *31*(4-5), 349-361.

Chen, L.-K., Yuan, R.-P., Ji, X.-J., Lu, X.-Y., Xiao, J., Tao, J.-B., Kang, X., Li, X., He, Z.-H., & Quan, S. (2021). Modular composite building in urgent emergency engineering projects: A case study of accelerated design and construction of Wuhan Thunder God Mountain/Leishenshan hospital to COVID-19 pandemic. *Automation in Construction*, *124*, 103555.

Chen, L., & Whyte, J. (2021). Understanding design change propagation in complex engineering systems using a digital twin and design structure matrix. *Engineering, construction and architectural management*.

Chen, W. (2020). *Rapid Construction Technology and General Contract Management for Huoshenshan Hospital* (W. Chen, Ed.). China Architecture & Building Press.

Chen, Y., Chowdhury, S. D., & Donada, C. (2019). Mirroring hypothesis and integrality: Evidence from Tesla Motors. *Journal of Engineering and Technology Management*, *54*, 41-55.

Chiu, M.-L. (2002). An organizational view of design communication in design collaboration. *Design studies*, *23*(2), 187-210.

Choi, J. O., Chen, X. B., & Kim, T. W. (2019). Opportunities and challenges of modular methods in dense urban environment. *International journal of construction management*, *19*(2), 93-105.

Choi, J. O., Shrestha, B. K., Kwak, Y. H., & Shane, J. S. (2020a). Critical success factors and enablers for facility design standardization of capital projects. *Journal of management in engineering*, *36*(5), 04020048.

Choi, J. O., Shrestha, B. K., Kwak, Y. H., & Shane, J. S. (2020b). Innovative technologies and management approaches for facility design standardization and modularization of capital projects. *Journal of management in engineering*, *36*(5), 04020042.

Choi, M., & Erikstad, S. O. (2017). A module configuration and valuation model for operational flexibility in ship design using contract scenarios. *Ships and Offshore Structures*, *12*(8), 1127-1135.

Chryssolouris, G. (2013). *Manufacturing systems: theory and practice*. Springer Science & Business Media.

Clarkson, P. J., & Hamilton, J. R. (2000). 'Signposting', a parameter-driven task-based model of the design process. *Research in Engineering Design*, *12*(1), 18-38.

Clough, I. (2022). The case for more modular facilities in the NHS. *British Journal of Healthcare Management*, *28*(Sup3), 3-11.

CNKI. *China National Knowledge Infrastructure (CNKI)*. Retrieved July 31 from https://www.cnki.net/

Colfer, L. J., & Baldwin, C. Y. (2016). The mirroring hypothesis: theory, evidence, and exceptions. *Industrial and Corporate Change*, *25*(5), 709-738.

Collins, R., Bechler, K., & Pires, S. (1997). Outsourcing in the automotive industry: from JIT to modular consortia. *European management journal*, *15*(5), 498-508.

Construction 2.0. (2018). The Government of Hong Kong SAR Development Bureau. https://www.hkc2.hk/booklet/Construction-2-0-en.pdf

Conway, M. E. (1968). How do committees invent. *Datamation*, *14*(4), 28-31.

Corbett, J. (1991). *Design for manufacture: strategies, principles, and techniques*. Addison Wesley publishing company.

Corbusier, L. (1923). Vers une Architecture (Towards a new Architecture). In: France.

Couper, R., Maxwell, D., & Aitchison, M. (2019). The Legacies of Manufacturing and Factories of Industrialised Construction. *Modular and Offsite Construction (MOC) Summit Proceedings*, 243-250.

Creswell, J. W. (2007). Qualitative Inquiry & Research Design Choosing Among Five Approaches. Sage Publications. *Thousand Oaks, CA*.

Creswell, J. W. (2009). Mapping the field of mixed methods research. In (Vol. 3, pp. 95-108): SAGE publications Sage CA: Los Angeles, CA.

Creswell, J. W., & Poth, C. N. (2016). *Qualitative inquiry and research design: Choosing among five approaches*. Sage publications.

Crotty, M. (2020). *The foundations of social research: Meaning and perspective in the research process*. Routledge.

Crowley, A. (1998). Construction as a manufacturing process: Lessons from the automotive industry. *Computers & Structures*, *67*(5), 389-400.

Da Rocha, C. G., & El Ghoz, H. B. (2019). A model for implementing product modularity in buildings design. *Engineering, construction and architectural management*, *27*(3), 680-699.

Da Rocha, C. G., Formoso, C. T., & Tzortzopoulos, P. (2015). Adopting product modularity in house building to support mass customisation. *Sustainability*, *7*(5), 4919-4937.

Da Rocha, C. G., & Kemmer, S. (2018). Integrating product and process design in construction. *Construction Management and Economics*, *36*(9), 535-543.

Da Rocha, C. G., & Koskela, L. (2020). Why is Product Modularity Underdeveloped in Construction? 28th Annual Conference of the International Group for Lean Construction (IGLC),

Dainty, A., Moore, D., & Murray, M. (2007). *Communication in construction: Theory and practice*. Routledge.

Davenport, T. H. (1993). *Process innovation: reengineering work through information technology*. Harvard Business Press.

Davies, R., & Harty, C. (2013). Implementing 'Site BIM': A case study of ICT innovation on a large hospital project. *Automation in Construction*, *30*, 15-24.

De Blok, C., Meijboom, B., Luijkx, K., Schols, J., & Schroeder, R. (2014). Interfaces in service modularity: A typology developed in modular health care provision. *Journal of operations management*, *32*(4), 175-189.

De Vaus, D. (2001). *Research design in social research*. Sage.

Di Giuda, G. M., Giana, P. E., Masera, G., Seghezzi, E., & Villa, V. (2019). A BIM-based approach to façade cladding optimization: Geometrical, economic, and production-control in a DfMA perspective. 2019 European conference on computing in construction,

Doran, D. (2004). Rethinking the supply chain: an automotive perspective. *Supply Chain Management: An International Journal*.

Doran, D., & Giannakis, M. (2011). An examination of a modular supply chain: a construction sector perspective. *Supply Chain Management: An International Journal*.

Doran, D., Hill, A., Hwang, K.-S., Jacob, G., & Group, O. R. (2007). Supply chain modularisation: Cases from the French automobile industry. *International journal of production economics*, *106*(1), 2-11.

Doran, D., & Roome, R. (2003). An evaluation of value-transfer within a modular supply chain. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, *217*(7), 521-527.

Dowsett, R., Harty, C., & Davies, R. (2017). The complete robot? The human-machine interface in temporary off-site construction work. 9th Nordic Conference on Construction Economics and Organization 13-14 June, 2017 at Chalmers University of Technology, Göteborg, SWEDEN,

Droge, C., Vickery, S. K., & Jacobs, M. A. (2012). Does supply chain integration mediate the relationships between product/process strategy and service performance? An empirical study. *International journal of production economics*, *137*(2), 250-262.

Easterby-Smith, M., Thorpe, R., & Jackson, P. R. (2012). *Management research*. Sage.

Eastman, C. M. (2012). *Design for X: concurrent engineering imperatives*. Springer Science & Business Media.

Eastman, C. M., Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*. John Wiley & Sons.

Easton, G. (2010). Critical realism in case study research. *Industrial marketing management*, *39*(1), 118-128.

Egan, J. (2002). Rethinking construction accelerating change-a consultation paper by the strategic forum for construction.

Eisenhardt, K., & Brown, S. (1999). Patching: Restitching business portfolios in dynamic markets-Kathleen M. Eisenhardt and Shona L. Brown respond. *Harvard business review*, *77*(5), 172-172.

Eisenhardt, K. M., & Graebner, M. E. (2007). Theory building from cases: Opportunities and challenges. *Academy of management journal*, *50*(1), 25-32.

Eisenhardt, K. M., Graebner, M. E., & Sonenshein, S. (2016). Grand challenges and inductive methods: Rigor without rigor mortis. In: Academy of Management Briarcliff Manor, NY.

Ellis, G. (2019). *The State of Healthcare Construction in 2019*. Construction Productivity Blog. Retrieved July 31 from https://blog.plangrid.com/2019/03/the-state-of-healthcare-construction-in-2019-infographic/

ElMaraghy, W., ElMaraghy, H., Tomiyama, T., & Monostori, L. (2012). Complexity in engineering design and manufacturing. *CIRP annals*, *61*(2), 793-814.

Emmatty, F. J., & Sarmah, S. (2012). Modular product development through platform-based design and DFMA. *Journal of Engineering Design*, *23*(9), 696-714.

Emmitt, S. (2010). *Managing interdisciplinary projects: a primer for architecture, engineering and construction*. Routledge.

Emmitt, S. (2014). *Design management for architects*. John Wiley & Sons.

Emmitt, S. (2016). BIM and the Future of Design Management. *Construction manager's Bim handbook*, 123.

Emmitt, S., & Ruikar, K. (2013). *Collaborative design management*. Routledge.

Eppinger, S. D., & Browning, T. R. (2012). *Design structure matrix methods and applications*. MIT press.

Eriksson, H., Sandberg, M., Jansson, G., & Lessing, J. (2021). Exploring Product Modularity in Residential Building Areas. *Buildings*, *11*(7), 281.

Fairclough, N. (2005). Peripheral vision: Discourse analysis in organization studies: The case for critical realism. *Organization studies*, *26*(6), 915-939.

Feitzinger, E., & Lee, H. L. (1997). Mass customization at Hewlett-Packard: the power of postponement. *Harvard business review*, *75*, 116-123.

Fellows, R. F., & Liu, A. M. (2021). *Research methods for construction*. John Wiley & Sons.

Fine, C. H., Golany, B., & Naseraldin, H. (2005). Modeling tradeoffs in three-dimensional concurrent engineering: a goal programming approach. *Journal of operations management*, *23*(3-4), 389-403.

Fisher, M. J., & Marshall, A. P. (2009). Understanding descriptive statistics. *Australian critical care*, *22*(2), 93-97.

Flyvbjerg, B. (2006). Five misunderstandings about case-study research. *Qualitative inquiry*, *12*(2), 219-245.

Flyvbjerg, B. (2021). Make Megaprojects More Modular. *Harvard business review*.

Forman, J., & Damschroder, L. (2007). Qualitative content analysis. In *Empirical methods for bioethics: A primer*. Emerald Group Publishing Limited.

Forza, C., Salvador, F., & Trentin, A. (2008). Form postponement effects on operational performance: a typological theory. *International Journal of Operations & Production Management*.

Fowler Jr, F. J. (2013). *Survey research methods*. Sage publications.

Fox, S., Marsh, L., & Cockerham, G. (2001). Design for manufacture: A strategy for successful application to buildings. *Construction Management and Economics*, *19*(5), 493-502.

Fronczek-Munter, A. (2016). *Usability Briefing for hospital design: Exploring user needs and experiences to improve complex buildings*. DTU Management Engineering.

Gadamer, H.-G. (2008). *Philosophical hermeneutics*. Univ of California Press.

Galletta, A. (2013). *Mastering the semi-structured interview and beyond: From research design to analysis and publication* (Vol. 18). NYU press.

Galunic, D. C., & Eisenhardt, K. M. (2001). Architectural innovation and modular corporate forms. *Academy of management journal*, *44*(6), 1229-1249.

Gamba, A., & Fusari, N. (2009). Valuing modularity as a real option. *Management science*, *55*(11), 1877-1896.

Gan, X., Chang, R., & Wen, T. (2018). Overcoming barriers to off-site construction through engaging stakeholders: A two-mode social network analysis. *Journal of Cleaner Production*, *201*, 735-747.

Gao, S., Jin, R., & Lu, W. (2020). Design for manufacture and assembly in construction: a review. *Building Research & Information*, *48*(5), 538-550.

Garud, R., & Kumaraswamy, A. (1995). Technological and organizational designs for realizing economies of substitution. *Strategic management journal*, *16*(S1), 93-109.

Gatenby, D. A., & Foo, G. (1990). Design for X (DFX): key to competitive, profitable products. *AT&T Technical Journal*, *69*(3), 2-13.

Gaur, S., & Tawalare, A. (2022). Investigating the role of BIM in stakeholder management: Evidence from a metro-rail project. *Journal of management in engineering*, *38*(1), 05021013.

Gbadamosi, A.-Q., Mahamadu, A.-M., Oyedele, L. O., Akinade, O. O., Manu, P., Mahdjoubi, L., & Aigbavboa, C. (2019). Offsite construction: Developing a BIM-Based optimizer for assembly. *Journal of Cleaner Production*, *215*, 1180-1190.

Gbadamosi, A.-Q., Mahamadu, A., Manu, P., Akinade, O., Sierra, F., Lam, T. T., & Alzaatreh, A. (2018). A BIM based approach for optimization of construction and assembly through material selection.

George, A. L., & Bennett, A. (2005). *Case studies and theory development in the social sciences*. mit Press.

Gershenson, J. K., Prasad, G., & Zhang, Y. (2003). Product modularity: definitions and benefits. *Journal of Engineering Design*, *14*(3), 295-313.

Gershenson, J. K., Prasad, G. J., & Allamneni, S. (1999). Modular product design: a life-cycle view. *Journal of Integrated Design and Process Science*, *3*(4), 13-26.

Gersick, C. J. (1991). Revolutionary change theories: A multilevel exploration of the punctuated equilibrium paradigm. *Academy of management review*, *16*(1), 10-36.

Gerth, R., Boqvist, A., Bjelkemyr, M., & Lindberg, B. (2013). Design for construction: utilizing production experiences in development. *Construction Management and Economics*, *31*(2), 135-150.

Ghezzi, C., Jazayeri, M., & Mandrioli, D. (1991). *Fundamentals of software engineering*. Prentice-Hall, Inc.

Gibb, A. G. (1999). *Off-site fabrication: prefabrication, pre-assembly and modularisation*. John Wiley & Sons.

Gillham, B. (2001). *Research interview*. Bloomsbury Publishing.

Gioia, D. A., Corley, K. G., & Hamilton, A. L. (2013). Seeking qualitative rigor in inductive research: Notes on the Gioia methodology. *Organizational Research Methods*, *16*(1), 15-31.

Glatthorn, A. A., & Joyner, R. L. (2005). *Writing the winning thesis or dissertation: A step-by-step guide*. Corwin Press.

Gokpinar, B., Hopp, W. J., & Iravani, S. M. (2010). The impact of misalignment of organizational structure and product architecture on quality in complex product development. *Management science*, *56*(3), 468-484.

Goodier, C., & Gibb, A. (2007). Future opportunities for offsite in the UK. *Construction Management and Economics*, *25*(6), 585-595.

Graham, I. (1994). *Object oriented methods*. Addison-Wesley Longman Publishing Co., Inc.

Graneheim, U. H., Lindgren, B.-M., & Lundman, B. (2017). Methodological challenges in qualitative content analysis: A discussion paper. *Nurse education today*, *56*, 29-34.

Groat, L. N., & Wang, D. (2013). *Architectural research methods*. John Wiley & Sons.

Groves, D. (2017). The construction industry’s productivity problem. *The Economist; The Economist Group: London, UK*.

Gualandris, J., & Kalchschmidt, M. (2013). Product and process modularity: improving flexibility and reducing supplier failure risk. *International Journal of Production Research*, *51*(19), 5757-5770.

Guenther, R., & Vittori, G. (2008). *Sustainable healthcare architecture*. John Wiley & Sons.

Gustafsson, J. (2017). Single case studies vs. multiple case studies: A comparative study. In.

Hall, D. M., Whyte, J. K., & Lessing, J. (2020). Mirror-breaking strategies to enable digital manufacturing in Silicon Valley construction firms: a comparative case study. *Construction Management and Economics*, *38*(4), 322-339.

Hamlyn, D. W. (1995). History of epistemology. *The Oxford companion to philosophy*, 242-245.

Hao, B., Feng, Y., & Frigant, V. (2017). Rethinking the ‘mirroring’hypothesis: implications for technological modularity, tacit coordination, and radical innovation. *R&D Management*, *47*(1), 3-16.

Harik, R. F., & Sahmrani, N. (2010). DFMA+, a quantitative DFMA methodology. *Computer-Aided Design and Applications*, *7*(5), 701-709.

Harrison, H., Birks, M., Franklin, R., & Mills, J. (2017). Case study research: Foundations and methodological orientations. Forum qualitative Sozialforschung/Forum: qualitative social research,

Harty, C., Throssell, D., Jeffrey, H., & Stagg, M. (2010). Implementing building information modeling: a case study of the Barts and the London hospitals. Proceedings of the International Conference on Computing in Civil and Building Engineering. Nottingham (UK): ICCBE,

Hayes, B. K., Heit, E., & Swendsen, H. (2010). Inductive reasoning. *Wiley interdisciplinary reviews: Cognitive science*, *1*(2), 278-292.

Hayes, R. H. (1979). The dynamics of process-product life cycle. *Harvard business review*, 127-136.

Henkel, J., Baldwin, C. Y., & Shih, W. (2013). IP modularity: Profiting from innovation by aligning product architecture with intellectual property. *California management review*, *55*(4), 65-82.

Hennink, M. M., Kaiser, B. N., & Marconi, V. C. (2017). Code saturation versus meaning saturation: how many interviews are enough? *Qualitative health research*, *27*(4), 591-608.

Hiller, J. (2016). Epistemological foundations of objectivist and interpretivist research.

Ho, R. (2006). *Handbook of univariate and multivariate data analysis and interpretation with SPSS*. Chapman and Hall/CRC.

Hofman, E., Voordijk, H., & Halman, J. (2009). Matching supply networks to a modular product architecture in the house-building industry. *Building Research & Information*, *37*(1), 31-42.

Hosseini, M. R., Martek, I., Zavadskas, E. K., Aibinu, A. A., Arashpour, M., & Chileshe, N. (2018). Critical evaluation of off-site construction research: A Scientometric analysis. *Automation in Construction*, *87*, 235-247.

Huberty, C. J., & Morris, J. D. (1992). Multivariate analysis versus multiple univariate analyses.

Innella, F., Arashpour, M., & Bai, Y. (2019). Lean methodologies and techniques for modular construction: chronological and critical review. *Journal of Construction Engineering and Management*, *145*(12), 04019076.

Ishii, K. (1998). Modularity: A key concept in product life-cycle engineering. *Handbook of Life-cycle Engineering*, 511-530.

Iskandar, K. A., Hanna, A. S., & Lotfallah, W. (2019). Modeling the performance of healthcare construction projects. *Engineering, Construction Architectural Management*.

Jacobs, J. (1961). The Death and Life of Great American Cities.

Jacobs, M., Droge, C., Vickery, S. K., & Calantone, R. (2011). Product and process modularity's effects on manufacturing agility and firm growth performance. *Journal of Product Innovation Management*, *28*(1), 123-137.

Jang, S., Jeong, Y., Lee, G., & Kang, Y. (2019). Enhancing Subcontractors' Participation in BIM-Based Design Coordination under a DBB Contract. *Journal of management in engineering*, *35*(6), 04019022.

Jang, S., & Lee, G. (2018). Process, productivity, and economic analyses of BIM–based multi-trade prefabrication—A case study. *Automation in Construction*, *89*, 86-98.

Jayaram, J., & Vickery, S. (2018). The role of modularity in the supply chain context: current trends and future research directions. In (Vol. 56, pp. 6568-6574): Taylor & Francis.

Jermsittiparsert, K., Joemsittiprasert, W., & Syazali, M. (2019). Impact of process and product modularity on competitive performance of Thailand manufacturing firms: mediating role of supply chain quality integration. *International Journal of Supply Chain Management*, *8*(3), 95-106.

Jewell, C., Flanagan, R., & Lu, W. (2014). The dilemma of scope and scale for construction professional service firms. *Construction Management and Economics*, *32*(5), 473-486.

Jiang, R., Mao, C., Hou, L., Wu, C., & Tan, J. (2018). A SWOT analysis for promoting off-site construction under the backdrop of China’s new urbanisation. *Journal of Cleaner Production*, *173*, 225-234.

Jin, R., Gao, S., Cheshmehzangi, A., & Aboagye-Nimo, E. (2018). A holistic review of off-site construction literature published between 2008 and 2018. *Journal of Cleaner Production*, *202*, 1202-1219.

Kao, C. C., Green, S. D., & Larsen, G. D. (2009). Emergent discourses of construction competitiveness: localized learning and embeddedness. *Construction Management and Economics*, *27*(10), 1005-1017.

Katila, R., Levitt, R. E., & Sheffer, D. (2018). Systemic innovation of complex one-off products: the case of green buildings. In *Organization design*. Emerald Publishing Limited.

Ketchen Jr, D. J., & Hult, G. T. M. (2002). To be Modular or not to be? Some Answers to the Question. *Academy of Management Perspectives*, *16*(2), 166-168.

Kim, J., Saidani, M., & Kim, H. M. (2021). Designing an optimal modular-based product family under intellectual property and sustainability considerations. *Journal of Mechanical Design*, *143*(11).

Kim, M.-K., McGovern, S., Belsky, M., Middleton, C., & Brilakis, I. (2016). A suitability analysis of precast components for standardized bridge construction in the United Kingdom. *Procedia engineering, 164*, 188-195.

Kim, S.-Y., Tuan, K. N., & Luu, V. T. (2016). Delay factor analysis for hospital projects in Vietnam. *KSCE Journal of Civil Engineering*, *20*(2), 519-529.

Kobus, R. L., Skaggs, R. L., Bobrow, M., Thomas, J., Payette, T. M., & Kliment, S. A. (2008). *Building type basics for healthcare facilities* (Vol. 13). John Wiley & Sons.

Kokkonen, A., & Alin, P. (2016). Practitioners deconstructing and reconstructing practices when responding to the implementation of BIM. *Construction Management and Economics, 34*(7-8), 578-591.

Koskela, L. (1992). *Application of the new production philosophy to construction* (Vol. 72). Citeseer.

Kremer, P. D. (2018). Design for Mass Customised Manufacturing and Assembly (DfMCMA): A framework for capturing off-site and on-site efficiencies in mass timber construction. *Mass Timber Construction Journal*, *1*(1), 9-13.

Krystofik, M., Wagner, J., & Gaustad, G. (2015). Leveraging intellectual property rights to encourage green product design and remanufacturing for sustainable waste management. *Resources, Conservation and Recycling*, *97*, 44-54.

Kuo, T.-C., Huang, S. H., & Zhang, H.-C. (2001). Design for manufacture and design for ‘X’: concepts, applications, and perspectives. *Computers & industrial engineering*, *41*(3), 241-260.

Kusiak, A. (2002). Integrated product and process design: a modularity perspective. *Journal of Engineering Design*, *13*(3), 223-231.

Lahtinen, M., Sirola, P., Peltokorpi, A., Aalto, L., Kyrö, R., Salonen, H., Ruohomäki, V., & Reijula, K. J. I. B. I. (2020). Possibilities for user-centric and participatory design in modular health care facilities. *12*(2), 100-114.

Langlois, R. N. (2002). Modularity in technology and organization. *Journal of economic behavior & organization, 49*(1), 19-37.

Lanigan, M. (1992). *Engineers in business: The principles of management and product design*. Addison Wesley Publishing Company.

Latham, S. M. (1994). Constructing the team.

Lather, J. I., Logan, T., Renner, K., & Messner, J. I. (2020). Implementation and evaluation of generative layout options using the graph theoretical approach for a hospital layout problem. *Journal of Computing in Civil Engineering*, *34*(4), 04020014.

Lavy, S., & Fernández-Solis, J. (2010). Complex healthcare facility management and lean construction. In (Vol. 3, pp. 3-6): SAGE Publications Sage CA: Los Angeles, CA.

Leaman, A., & Bordass, B. (1993). Building design, complexity and manageability. *Facilities*.

Lee, S., Georgoulas, C., & Bock, T. (2014). Towards 3-D shape restructuring for rapid prototyping of joining interface system. ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction,

Leech, N., & Onwuegbuzie, A. (2008). Horizonalization. *The SAGE encyclopedia of qualitative research methods*, *1*, 400-401.

Li, Q., Chong, H.-Y., Lee, C.-Y., & Zhang, Y. (2021). BIM's Formal and Informal Collaborative Networks in Traditional Procurement: Insights from the Construction Phase of a Hospital Case Study. *Journal of management in engineering*, *37*(6), 05021008.

Lin, Y.-C., Chen, Y.-P., Yien, H.-W., Huang, C.-Y., & Su, Y.-C. (2018). Integrated BIM, game engine and VR technologies for healthcare design: A case study in cancer hospital. *Advanced Engineering Informatics*, *36*, 130-145.

Love, P. E., & Ika, L. A. (2021). Making Sense of Hospital Project (Mis) Performance: Over Budget, Late, Time and Time Again—Why? And What Can Be Done About It? *Engineering*.

Lu, S. C.-Y., & Suh, N.-P. (2009). Complexity in design of technical systems. *CIRP annals*, *58*(1), 157-160.

Lu, W., Chen, K., Xue, F., & Pan, W. (2018). Searching for an optimal level of prefabrication in construction: An analytical framework. *Journal of Cleaner Production*, *201*, 236-245.

Lu, W., Ye, K., Flanagan, R., & Jewell, C. (2013). Developing construction professional services in the international market: SWOT analysis of China. *Journal of management in engineering*, *29*(3), 302-313.

Lundin, R. A., & Söderholm, A. (1995). A theory of the temporary organization. *Scandinavian Journal of management*, *11*(4), 437-455.

Luo, H., Liu, J., Li, C., Chen, K., & Zhang, M. (2020). Ultra-rapid delivery of specialty field hospitals to combat COVID-19: Lessons learned from the Leishenshan Hospital project in Wuhan. *Automation in Construction*, *119*, 103345.

MacCormack, A., Baldwin, C., & Rusnak, J. (2012). Exploring the duality between product and organizational architectures: A test of the "mirroring" hypothesis. *Research policy*, *41*(8), 1309-1324.

MacCormack, A., Rusnak, J., & Baldwin, C. Y. (2007). The impact of component modularity on design evolution: Evidence from the software industry. *Harvard Business School Technology & Operations Mgt. Unit Research Paper*(08-038).

Machado, M., Underwood, J., & Fleming, A. (2016). Implementing BIM to streamline a design, manufacture, and fitting workflow: a case study on a fit-out SME in the UK. *International Journal of 3-D Information Modeling (IJ3DIM)*, *5*(3), 31-46.

Madni, A. M., & Sievers, M. (2014). Systems integration: Key perspectives, experiences, and challenges. *Systems Engineering*, *17*(1), 37-51.

Maier, J. R., & Fadel, G. M. (2006). Understanding the complexity of design. In *Complex Engineered Systems* (pp. 122-140). Springer.

Mao, C., Shen, Q., Pan, W., & Ye, K. (2015). Major barriers to off-site construction: The developer's perspective in China. *Journal of management in engineering*, *31*(3), 04014043.

Maskell, B. H. (1991). *Performance measurement for world class manufacturing: A model for American companies*. CRC press.

McComb, C., & Jablokow, K. (2022). A conceptual framework for multidisciplinary design research with example application to agent-based modeling. *Design studies*, *78*, 101074.

Meng, Q., Zhang, Y., Li, Z., Shi, W., Wang, J., Sun, Y., Xu, L., & Wang, X. (2020). A review of integrated applications of BIM and related technologies in whole building life cycle. *Engineering, construction and architectural management*, *27*(8), 1647-1677.

Merschbrock, C., Hosseini, M. R., Martek, I., Arashpour, M., & Mignone, G. (2018). Collaborative role of sociotechnical components in BIM-based construction networks in two hospitals. *Journal of management in engineering*, *34*(4), 05018006.

Merschbrock, C., & Munkvold, B. E. (2015). Effective digital collaboration in the construction industry–A case study of BIM deployment in a hospital construction project. *Computers in Industry*, *73*, 1-7.

Mignone, G., Hosseini, M. R., Chileshe, N., & Arashpour, M. (2016). Enhancing collaboration in BIM-based construction networks through organisational discontinuity theory: a case study of the new Royal Adelaide Hospital. *Architectural Engineering and Design Management*, *12*(5), 333-352.

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook*. sage.

Mills, G., Goodier, C., Kingston, J., Astley, P., Symons, A., Tan, T., & Sherwood, C. (2020). Challenging Space Frontiers in Hospitals: Accelerating capabilities and advancing platforms for modern hospital manufacture.

Mills, G. R. (2013). *Values and value in design* Loughborough University].

Mills, G. R., Phiri, M., Erskine, J., & Price, A. D. (2015). Rethinking healthcare building design quality: an evidence-based strategy. *Building Research & Information*, *43*(4), 499-515.

Mitchell, J. C. (2006). Case and situation analysis. *The Manchester School: Practice and ethnographic praxis in anthropology*, 23-42.

Mittal, Y. K., Paul, V. K., Rostami, A., Riley, M., & Sawhney, A. (2020). Delay factors in construction of healthcare infrastructure projects: a comparison amongst developing countries. *Asian Journal of Civil Engineering*, 1-13.

Montali, J., Overend, M., Pelken, P. M., & Sauchelli, M. (2018). Knowledge-Based Engineering in the design for manufacture of prefabricated façades: current gaps and future trends. *Architectural Engineering and Design Management*, *14*(1-2), 78-94.

Montali, J., Sauchelli, M., Jin, Q., & Overend, M. (2019). Knowledge-rich optimisation of prefabricated façades to support conceptual design. *Automation in Construction*, *97*, 192-204.

Morse, J. M. (1994). *Critical issues in qualitative research methods*. Sage.

Moser, C. A., & Kalton, G. (2017). *Survey methods in social investigation*. Routledge.

Moustakas, C. (1994). *Phenomenological research methods*. Sage publications.

Niiniluoto, I. (1999). Defending abduction. *Philosophy of science*, *66*(S3), S436-S451.

Noor, K. B. M. (2008). Case study: A strategic research methodology. *American journal of applied sciences*, *5*(11), 1602-1604.

Novikov, A. M., & Novikov, D. A. (2013). *Research methodology: From philosophy of science to research design* (Vol. 2). CRC Press.

O'Rourke, L. (2013). The future of DfMA is the future of construction. *Engineering Excellence Journal*, *77*, 76.

Oh, M., Lee, J., Hong, S. W., & Jeong, Y. (2015). Integrated system for BIM-based collaborative design. *Automation in Construction*, *58*, 196-206.

Orlowski, K., Shanaka, K., & Mendis, P. (2018). Design and development of weatherproof seals for prefabricated construction: A methodological approach. *Buildings*, *8*(9), 117.

Pan, W., Dainty, A., & Gibb, A. (2004). Encouraging appropriate use of Offsite Production (OSP): perspectives of designers.

Pan, W., Gibb, A. G., & Dainty, A. R. (2007). Perspectives of UK housebuilders on the use of offsite modern methods of construction. *Construction Management and Economics*, *25*(2), 183-194.

Pan, W., Gibb, A. G., & Dainty, A. R. (2008). Leading UK housebuilders' utilization of offsite construction methods. *Building Research & Information*, *36*(1), 56-67.

Pan, W., Gibb, A. G., & Dainty, A. R. (2012). Strategies for integrating the use of off-site production technologies in house building.

Pan, W., Parker, D., & Pan, M. (2023). Problematic Interfaces and Prevention Strategies in Modular Construction. *Journal of management in engineering*, *39*(2), 05023001.

Pan, W., & Sidwell, R. (2011). Demystifying the cost barriers to offsite construction in the UK. *Construction Management and Economics*, *29*(11), 1081-1099.

Pan, W., Yang, Y., Zhang, Z., & Chan, S. (2019). Modularisation for modernisation: A strategy paper rethinking Hong Kong construction. *Modularisation for Modernisation: A Strategy Paper Rethinking Hong Kong Construction*.

Pan, W., & Zhang, Z. (2022). Evaluating Modular Healthcare Facilities for COVID-19 Emergency Response—A Case of Hong Kong. *Buildings*, *12*(9), 1430.

Pandremenos, J., Paralikas, J., Salonitis, K., & Chryssolouris, G. (2009). Modularity concepts for the automotive industry: a critical review. *CIRP Journal of Manufacturing Science and Technology*, *1*(3), 148-152.

Parnas, D. L. (1972). On the criteria to be used in decomposing systems into modules. In *Pioneers and their contributions to software engineering* (pp. 479-498). Springer.

Parraguez, P., Piccolo, S. A., Perišić, M. M., Štorga, M., & Maier, A. M. (2019). Process modularity over time: modeling process execution as an evolving activity network. *IEEE Transactions on engineering management*, *68*(6), 1867-1879.

Paul, G. (1993). Approaches to abductive reasoning: an overview. *Artificial intelligence review*, *7*(2), 109-152.

Pearce, D. (2003). Environment and business: Socially responsible but privately profitable? In. Profile Books.

Pearce, D. W. (2003). *The social and economic value of construction: The construction industry's contribution to sustainable development, 2003*. Construction Industry Research and Innovation Strategy Panel.

Pero, M., Abdelkafi, N., Sianesi, A., & Blecker, T. (2010). A framework for the alignment of new product development and supply chains. *Supply Chain Management: An International Journal*.

Pero, M., Stößlein, M., & Cigolini, R. (2015). Linking product modularity to supply chain integration in the construction and shipbuilding industries. *International journal of production economics*, *170*, 602-615.

Phillips, J., Phillips, A., & Phillips, A. (1999). Management of modular projects: a templating approach. *Project management journal*, *30*(4), 33-41.

Pikas, E., Koskela, L., Sapountzis, S., Dave, B., & Owen, R. (2011). Overview of building information modelling in healthcare projects. HaCIRIC 11 Conference proceedings,

Pires, S. R. (1998). Managerial implications of the modular consortium model in a Brazilian automotive plant. *International Journal of Operations & Production Management*.

Quan, X. (2006). Hierarchical Modular R&D Structure and Intellectual Property Protection: Evidence from Multinational R&D labs in China. 2006 IEEE International Conference on Management of Innovation and Technology,

Quan, X., & Chesbrough, H. (2009). Hierarchical segmentation of R&D process and intellectual property protection: Evidence from multinational R&D laboratories in China. *IEEE Transactions on engineering management*, *57*(1), 9-21.

Rausch, C., Nahangi, M., Perreault, M., Haas, C. T., & West, J. (2017). Optimum assembly planning for modular construction components. *Journal of Computing in Civil Engineering*, *31*(1), 04016039.

Renier, B., & Volker, L. (2008). The architect as a system integrator. 24th Annual ARCOM Conference,

Ro, Y. K., Liker, J. K., & Fixson, S. K. (2007). Modularity as a strategy for supply chain coordination: the case of US auto. *IEEE Transactions on engineering management*, *54*(1), 172-189.

Rojas Arciniegas, A. J., & Kim, H. M. (2012). Incorporating security considerations into optimal product architecture and component sharing decision in product family design. *Engineering Optimization*, *44*(1), 55-74.

Sacks, R., & Pikas, E. (2021). Foundational concepts for BIM. In *BIM Teaching and Learning Handbook* (pp. 5-22). Routledge.

Safaa, Y. P., Hatmoko, J. U. D., & Purwanggono, B. (2019). Evaluation of the use of prefabricated bridge elements with Design for Manufacture and Assembly (DfMA) criteria. MATEC Web of Conferences,

Saldaña, J. (2021). *The coding manual for qualitative researchers*. sage.

Salmon, W. C. (2017). *The foundations of scientific inference*. University of Pittsburgh Press.

Salvador, F. (2007). Toward a product system modularity construct: literature review and reconceptualization. *IEEE Transactions on engineering management*, *54*(2), 219-240.

Salvador, F., Forza, C., & Rungtusanatham, M. (2002). Modularity, product variety, production volume, and component sourcing: theorizing beyond generic prescriptions. *Journal of operations management*, *20*(5), 549-575.

Salvador, F., Rungtusanatham, M., & Forza, C. (2004). Supply-chain configurations for mass customization. *Production Planning & Control*, *15*(4), 381-397.

Samarasinghe, T., Mendis, P., Aye, L., & Vassos, T. (2016). Applications of design for excellence in prefabricated building services systems. Proceedings of the 7th International Conference on Sustainable Built Environment (ICSBE), Kandy, Sri Lanka,

Sanchez, R., & Mahoney, J. T. (1996). Modularity, flexibility, and knowledge management in product and organization design. *Strategic management journal*, *17*(S2), 63-76.

Saunders, B., Sim, J., Kingstone, T., Baker, S., Waterfield, J., Bartlam, B., Burroughs, H., & Jinks, C. (2018). Saturation in qualitative research: exploring its conceptualization and operationalization. *Quality & quantity*, *52*, 1893-1907.

Saunders, M., Lewis, P., & Thornhill, A. (2009). *Research methods for business students*. Pearson education.

Schilling, M. A. (2000). Toward a general modular systems theory and its application to interfirm product modularity. *Academy of management review*, *25*(2), 312-334.

Schilling, M. A., & Steensma, H. K. (2001). The use of modular organizational forms: An industry-level analysis. *Academy of management journal*, *44*(6), 1149-1168.

Schmidt, C. (2004). The analysis of semi-structured interviews. *A companion to qualitative research*, *253*(41), 258.

Schönbeck, P., Löfsjögård, M., & Ansell, A. (2020). Framework for change control in healthcare construction projects compared to current practice. *International journal of construction management*, 1-8.

Schreier, M. (2012). *Qualitative content analysis in practice*. Sage publications.

Sebastian, R. (2011). Changing roles of the clients, architects and contractors through BIM. *Engineering, construction and architectural management*.

Shields, P. M., & Rangarajan, N. (2013). *A playbook for research methods: Integrating conceptual frameworks and project management*. New Forums Press.

Simkin, R. D., Seto, K. C., McDonald, R. I., & Jetz, W. (2022). Biodiversity impacts and conservation implications of urban land expansion projected to 2050. *Proceedings of the National Academy of Sciences*, *119*(12), e2117297119.

Simon, H. A. (1962). The Architecture of Complexity. *Proceedings of the American Philosophical Society*, *106*(6), 467-482.

Smith, R. E., & Quale, J. D. (2017). *Offsite architecture: Constructing the future*. Taylor & Francis.

Soliman-Junior, J., Tzortzopoulos, P., Baldauf, J. P., Pedo, B., Kagioglou, M., Formoso, C. T., & Humphreys, J. (2021). Automated compliance checking in healthcare building design. *Automation in Construction*, *129*, 103822.

Sonego, M., Echeveste, M. E. S., & Debarba, H. G. (2018). The role of modularity in sustainable design: A systematic review. *Journal of Cleaner Production*, *176*, 196-209.

Sonnenwald, D. H. (1996). Communication roles that support collaboration during the design process. *Design studies*, *17*(3), 277-301.

Sorkun, M. F., & Furlan, A. (2017). Product and organizational modularity: a contingent view of the mirroring hypothesis. *European Management Review*, *14*(2), 205-224.

Sosa, M. E., Eppinger, S. D., & Rowles, C. M. (2004). The misalignment of product architecture and organizational structure in complex product development. *Management science*, *50*(12), 1674-1689.

Soyer, A., Asan, U., & Eriş, Ö. U. (2019). Toward a Conceptualization of Organizational Modularity. In *Handbook of Research on Contemporary Approaches in Management and Organizational Strategy* (pp. 355-382). IGI Global.

Stake, R. E. (1978). The case study method in social inquiry. *Educational researcher*, *7*(2), 5-8.

Starr, M. K. (1965). Modular production-a new concept. *Harv. Bus. Rev.*, 131-142.

Sturgeon, T. J. (2002). Modular production networks: a new American model of industrial organization. *Industrial and Corporate Change*, *11*(3), 451-496.

Subramanian, R., Ferguson, M. E., & Beril Toktay, L. (2013). Remanufacturing and the component commonality decision. *Production and Operations management*, *22*(1), 36-53.

Succar, B. (2009). Building information modelling framework: A research and delivery foundation for industry stakeholders. *Automation in construction*, *18*(3), 357-375.

Suh, N. P. (2005). *Complexity: theory and applications*. Oxford university press.

Swift, K. G., & Brown, N. J. (2003). Implementation strategies for design for manufacture methodologies. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *217*(6), 827-833.

Tan, T., Chen, K., Xue, F., & Lu, W. (2019). Barriers to Building Information Modeling (BIM) implementation in China's prefabricated construction: An interpretive structural modeling (ISM) approach. *Journal of Cleaner Production*, *219*, 949-959.

Tan, T., Mills, G., Hu, J., & Papadonikolaki, E. (2021). Integrated approaches to design for manufacture and assembly: A case study of Huoshenshan hospital to combat COVID-19 in Wuhan, China. *Journal of management in engineering*, *37*(6), 05021007.

Tan, T., Mills, G., Papadonikolaki, E., Lu, W., & Chen, K. (2020). BIM-enabled design for manufacture and assembly.

Tang, J. M. L. (2020). *A qualitative study and thematic analysis concerning the applicability and efficacy of service design processes applied to healthcare service innovation* University of Wales Trinity Saint David].

Taylor, J. E., & Levitt, R. (2007). Innovation alignment and project network dynamics: An integrative model for change. *Project management journal*, *38*(3), 22-35.

Tee, R., Davies, A., & Whyte, J. (2019). Modular designs and integrating practices: Managing collaboration through coordination and cooperation. *Research policy*, *48*(1), 51-61.

Thomas, G. (2011). A typology for the case study in social science following a review of definition, discourse, and structure. *Qualitative inquiry*, *17*(6), 511-521.

Thomlison, B. (2001). Descriptive studies. *The handbook of social work research methods*, *131*.

Tillmann, P. A., Tzortzopoulos, P., & Formoso, C. T. (2010). Redefining healthcare infrastructure: moving toward integrated solutions. *HERD: Health Environments Research & Design Journal*, *3*(2), 84-96.

Tommelein, I. D. (1998). Pull-driven scheduling for pipe-spool installation: Simulation of lean construction technique. *Journal of Construction Engineering and Management*, *124*(4), 279-288.

Tresidder, M., & White, P. (2018). Briefing: Design for manufacture and off-site construction at Woolston Wastewater Treatment Works (UK). *Proceedings of the Institution of Civil Engineers-Management, Procurement and Law*, *171*(4), 137-140.

Trochim, W. M. (2006). Descriptive statistics.

Trochim, W. M., & Donnelly, J. P. (2001). *Research methods knowledge base* (Vol. 2). Atomic Dog Pub. Macmillan Publishing Company, New York.

Tsoukas, H. (2009). Craving for generality and small-N studies: A Wittgensteinian approach towards the epistemology of the particular in organization and management studies. *The Sage handbook of organizational research methods*, 285-301.

Tu, Q., Vonderembse, M. A., Ragu-Nathan, T. S., & Ragu-Nathan, B. (2004). Measuring modularity-based manufacturing practices and their impact on mass customization capability: a customer-driven perspective. *Decision Sciences*, *35*(2), 147-168.

Tunisini, A. (2006). Modularizzazione del prodotto e processi di creazione del valore nei mercati industriali. *Urbino, Italy: University of Economics*.

Turner, J. R., & Müller, R. (2003). On the nature of the project as a temporary organization. *International journal of project management*, *21*(1), 1-8.

Turner, J. R., & Simister, S. J. (2001). Project contract management and a theory of organization. *International journal of project management*, *19*(8), 457-464.

Tutt, D., Harty, C., Smith, S., & Ahiaga-Dagbui, D. (2013). Journeys through the CAVE: The use of 3D immersive environments for client engagement practices in hospital design. Proceedings 29th Annual ARCOM Conference, Association of Researchers in Construction Management, Reading,

Ulrich, K. (1994). Fundamentals of product modularity. In *Management of Design* (pp. 219-231). Springer.

Ulrich, K. (1995). The role of product architecture in the manufacturing firm. *Research policy*, *24*(3), 419-440.

Vaz-Serra, P., Wasim, M., & Egglestone, S. (2021). Design for manufacture and assembly: A case study for a prefabricated bathroom wet wall panel. *Journal of Building Engineering*, *44*, 102849.

Verderber, S. (2010). *Innovations in hospital architecture*. Routledge.

Verderber, S. (2015). *Innovations in transportable healthcare architecture*. Routledge.

Vickery, S. K., Koufteros, X., Dröge, C., & Calantone, R. (2016). Product modularity, process modularity, and new product introduction performance: does complexity matter? *Production and Operations management*, *25*(4), 751-770.

Voordijk, H., Meijboom, B., & de Haan, J. (2006). Modularity in supply chains: a multiple case study in the construction industry. *International Journal of Operations & Production Management*.

Voss, C. A., & Hsuan, J. (2009). Service architecture and modularity. *Decision Sciences*, *40*(3), 541-569.

Wada, K., Akimoto, K., Sano, F., Oda, J., & Homma, T. (2012). Energy efficiency opportunities in the residential sector and their feasibility. *Energy*, *48*(1), 5-10.

Wamelink, J., Koolwijk, J., & van Doorn, A. (2012). Integrated project delivery: The designer as integrator. Management of Construction: Research to Practice (MCRP) Conference Proceedings of the International Congress on Construction management research, Montreal, Canada, 26-29 June, 2012, Wang, H., Lu, W., Söderlund, J., & Chen, K. (2018). The interplay between formal and informal institutions in projects: A social network analysis. *Project management journal*, *49*(4), 20-35.

Wang, W., Fu, Y., Gao, J., Shang, K., Gao, S., Xing, J., Ni, G., Yuan, Z., Qiao, Y., & Mi, L. (2021). How the COVID-19 outbreak affected organizational citizenship behavior in emergency construction megaprojects: Case study from two emergency hospital projects in Wuhan, China. *Journal of management in engineering*, *37*(3), 04021008.

Warszawski, A. (2003). *Industrialized and automated building systems: A managerial approach*. Routledge.

Weick, K. E. (1976). Educational organizations as loosely coupled systems. *Administrative science quarterly*, 1-19.

Weissman, G. E., Crane-Droesch, A., Chivers, C., Luong, T., Hanish, A., Levy, M. Z., Lubken, J., Becker, M., Draugelis, M. E., & Anesi, G. L. (2020). Locally informed simulation to predict hospital capacity needs during the COVID-19 pandemic. *Annals of internal medicine*, *173*(1), 21-28.

WHO. (2019). *World health statistics 2019: monitoring health for the SDGs, sustainable development goals*. (9241565705). World Health Organization Retrieved from http://www.who.int/gho/publications/world_health_statistics/2016/en/

WHO. (2023). *Hospitals*. https://www.who.int/health-topics/hospitals#tab=tab_3

Whyte, J. (2016). The future of systems integration within civil infrastructure: A review and directions for research. INCOSE International Symposium,

Williams, M. (2016). *Key concepts in the philosophy of social research*. Sage.

Winch, G. (2003). Models of manufacturing and the construction process: the genesis of re-engineering construction. *Building Research & Information*, *31*(2), 107-118.

Woiceshyn, J., & Daellenbach, U. (2018). Evaluating inductive vs deductive research in management studies: Implications for authors, editors, and reviewers. *Qualitative Research in Organizations and Management: An International Journal*.

Wolstenholme, A., Austin, S. A., Bairstow, M., Blumenthal, A., Lorimer, J., McGuckin, S., Jones, S. R., Ward, D., Whysall, D., & Le Grand, Z. (2009). Never waste a good crisis: a review of progress since Rethinking Construction and thoughts for our future.

Wolters, M. (2002). *The business of modularity and the modularity of business*.

Woo, J., & O'Connor, J. T. (2021). Mitigation Strategies to Prevent Engineering Design Quality Defects. *Journal of management in engineering*, *37*(3), 04021007.

Worren, N., Moore, K., & Cardona, P. (2002). Modularity, strategic flexibility, and firm performance: a study of the home appliance industry. *Strategic management journal*, *23*(12), 1123-1140.

Wortmann, T., & Tunçer, B. (2017). Differentiating parametric design: Digital workflows in contemporary architecture and construction. *Design studies*, *52*, 173-197.

Wright, S., Barlow, J., & Roehrich, J. K. (2019). Public-Private Partnerships for Health Services: Construction, Protection and Rehabilitation of Critical Healthcare Infrastructure in Europe. In *Public Private Partnerships* (pp. 125-151). Springer.

Wynn, D., Eckert, C., & Clarkson, P. J. (2005). Abstracting complexity for design planning. *Complexity in Design and Engineering*.

Yin, R. K. (2017). *Case study research and applications: Design and methods*. Sage publications.

Young, R. (2009). Developments in service design thinking and practice. In *Embracing Complexity in Design* (pp. 177-192). Routledge.

Yuan, Z., Sun, C., & Wang, Y. (2018). Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings. *Automation in Construction*, *88*, 13-22.

Zhong, R. Y., Peng, Y., Xue, F., Fang, J., Zou, W., Luo, H., Ng, S. T., Lu, W., Shen, G. Q., & Huang, G. Q. (2017). Prefabricated construction enabled by the Internet-of-Things. *Automation in Construction*, *76*, 59-70.

Žukauskas, P., Vveinhardt, J., & Andriukaitienė, R. (2018). Philosophy and paradigm of scientific research. *Management culture and corporate social responsibility*, *121*, 139.

Appendix

Appendix 1 – Survey in Chinese

本问卷包含 22 道，填写时间将不超过 5 分钟。该研究严格保证每位调查对象个人信息的私密性，调查结果仅供学术研究，不存在任何商业目的。感谢对本次调查的贡献，您的意见将至关重要！如果对本研究有任何问题，可以联系 ucqbtt2@ucl.ac.uk[段落说明]

第 1 部分-背景[段落说明]

1. 请描述您所在的机构类型[单选题]

- □ 业主方
- □ 设计方
- □ 咨询服务方
- □ 施工承包方
- □ 建筑设备供应商
- □ 医疗设备供应商
- □ 装饰材料供应商
- □ 运营服务方
- □ +其他____

2. 请描述您的职务类型[单选题]

- □ 医院项目前期策划
- □ 医院设备配置与管理
- □ 项目规划设计
- □ 医院工程建设
- □ 项目实施管理
- □ 医院运营管理
- □ +其他____

3. 您所在机构主要参与医疗建设的哪些阶段[多选题]

- □ 规划
- □ 设计
- □ 制造
- □ 施工
- □ 运营
- □ +其他____

4. 您在建筑行业从事多少年工作[单选题]

- □ 0-5
- □ 6-10
- □ 11-15
- □ 16-20
- □ ＞20

5. 您所在机构的规模有多大[单选题]

- □ 微型 (1-10 人)
- □ 小型 (11-50 人)
- □ 中型 (51-250 人)
- □ 大型 (＞250 人)

6. 您所在机构的名称是什么（选填）[单行文本题]

第 2 部分-采用建筑工业化和数字技术的现状[段落说明]

7. 您的机构在医疗项目中采用了哪些建筑工业化的策略[矩阵量表题](建筑工业化，指通过现代化的制造、运输、安装和科学管理的生产方式，来代替传统建筑业中分散的、低水平的、低效率的手工业生产方式。它的主要标志是建筑设计标准化、构配件生产工厂化，施工机械化和组织管理科学化。)

0~4

- 大部分的建筑构件在工厂加工制造
- 施工现场采用装配式拼装的方式
- 建立了标准化的构件体系
- 利用机械或机器人进行施工建造
- 全生产过程的信息化管理体系
- 设计了装配式的建筑结构体系
- 采用标准化的建筑设计方法

8. 您的机构在医疗项目中采用了哪些提高制造和装配能力的设计策略[矩阵量表题]

0~4

- 对设计进行错误检查
- 设计时考虑更容易制造建筑构件的方案
- 设计时考虑使用更简单和易于操作的建筑构件
- 设计时考虑到预先确定的建筑构件组装技术
- 设计多功能和多用途零件/建筑构件
- 考虑模块化设计
- 考虑针对机械化或自动化装配的设计
- 使用标准化或现成的组件
- 使用相似的材料

- 使用环保材料
- 减少零件数量
- 最小化连接构件的数量
- 标准化连接构件的类型
- 尽量减少易碎零件/建筑构件的使用
- 提高容错度和不过度指定误差范围

9. 您的机构当前有多少比例的医院项目采用了建筑工业化策略[单选题]

- □ 0-20%
- □ 20-40%
- □ 40-60%
- □ 60-80%
- □ 80-100%

10. 相比传统施工方式的医院建设，采用建筑工业化策略带来了项目层面很大程度的改变[矩阵量表题]

-2~2

- 减少了人力成本
- 增强了生产安全
- 提升了产品品质
- 减少了工程周期
- 减少了资源浪费
- 减少了造价成本

===分页===

11. 您的机构在医疗项目中采用了哪些数字化技术[矩阵量表题]

0~4

- 建筑信息模型（BIM）
- 虚拟现实（VR） / 增强现实（AR）
- 物联网 / 传感器
- 3D 打印 / 增材制造
- 区块链技术
- 机器人 (臂) / 无人机
- 数字孪生
- 人工智能 / 机器学习
- 云计算
- 5G 网络

12. 您的机构当前有多少比例的医院项目采用了数字化技术[单选题]

- □ 0-20%
- □ 20-40%
- □ 40-60%
- □ 60-80%
- □ 80-100%

13. 相比传统施工方式的医院建设，采用数字技术带来了项目层面很大程度的改变[矩阵量表题]

-2~2

- 减少了人力成本
- 增强了生产安全
- 提升了产品品质
- 减少了工程周期
- 减少了资源浪费
- 减少了造价成本

===分页===

第 3 部分-采用建筑工业化和数字技术的采用因素[段落说明]

14. 在医院建设中，影响您的机构是否采用建筑工业化的主要因素[矩阵量表题](建筑工业化，指通过现代化的制造、运输、安装和科学管理的生产方式，来代替传统建筑业中分散的、低水平的、低效率的手工业生产方式。它的主要标志是建筑设计标准化、构配件生产工厂化，施工机械化和组织管理科学化。)

-2~2

- 可以提高产品质量
- 可以提高公司竞争力
- 与当前业务兼容性好
- 技术难度不复杂
- 各专业协同工作的机制不复杂
- 公司管理层支持建筑工业化
- 公司具备建筑工业化所需的软硬件资源和团队
- 公司具备快速变革适应新技术的能力
- 来自竞争对手使用建筑工业化路径的压力
- 客户希望使用建筑工业化方式
- 是政策和行业的趋势要求

- 需要较少的持续投资和软硬件支持
- 使得收益增加
- 使得业务量增加
- 建筑工业化策略实现简单
- 可以提高生产效率
- 可以提高顾客满意度
- 公司愿意采纳和支持建筑工业化

===分页===

15. 在医院建设中，影响您的机构是否采用 BIM 的主要因素[矩阵量表题](建筑信息模型\（BIM\）技术是一种应用于工程设计、建造、管理的数据化工具，通过对建筑的数据化、信息化模型整合，在项目策划、运行和维护的全生命周期过程中进行共享和传递。)

-2~2

- 可以提高产品质量
- 可以提高公司竞争力
- 与当前业务兼容性好
- 技术难度不复杂
- 各专业协同工作的机制不复杂
- 公司管理层支持 BIM
- 公司具备 BIM 所需的软硬件资源和团队
- 公司具备快速变革适应新技术的能力
- 来自竞争对手使用 BIM 的压力
- 客户希望使用 BIM 方式
- 是政策和行业的趋势要求
- 需要较少的持续投资和软硬件支持
- 使得收益增加
- 使得业务量增加
- BIM 实现简单
- 可以提高生产效率
- 可以提高顾客满意度
- 公司愿意采纳和支持 BIM

===分页===

第 4 部分-采用建筑工业化和数字技术的适当策略[段落说明]

16. 您的机构在医疗建设中采取了与其他建筑类型（如住宅、办公）不同的建筑工业化设计和建造方法[量表题]

-2~2

17. 您的机构采取了什么策略来减少医疗项目中实施建筑工业化的障碍?[多行文本题]

18. 对于整个医疗建设领域，您认为有必要提升建筑工业化的实施比例[量表题]

-2~2

19. 您的机构在医疗建设中采取了与其他建筑类型（如住宅、办公）不同的 BIM 设计和建造方法[量表题]

-2~2

20. 您的机构采取了什么策略来减少医疗项目中实施 BIM 的障碍?[多行文本题]

21. 对于整个医疗建设领域，您认为有必要提升 BIM 的使用比例[量表题]

-2~2

22. 您是否愿意参与后续访谈研究?[单选题]

否，我不想参与

+是，我的微信或手机联系方式是____

中国医院建设中的工业化和数字化技术发展

本问卷包含 23 道题，填写时间将不超过 10 分钟。该研究严格保证每位调查对象个人信息的私密性，所产生的数据将不具有可识别的组织和个人信息。调查结果仅供学术研究，不存在其它商业目的。

感谢对本次调查的贡献，您的意见将至关重要。您的真实回答对我们的研究至关重要！对您的支持与合作，我们表示由衷的感谢！如对本研究有任何问题，可以联系 tan.tan@ucl.ac.uk。

第 1 部分 – 背景

本节希望您提供有关您职务和机构的一些简单信息。

1. 请描述您所在的机构类型

- □ 业主方
- □ 建筑设计
- □ 咨询服务
- □ 施工承包
- □ 建筑设备
- □ 医疗设备
- □ 装饰材料
- □ 运营服务
- □ 其他

2. 请描述您的职务类型:

- □ 医院项目前期策划（项目前期策划、医院战略规划、医疗业务规划、医疗工艺流程规划等）
- □ 医院设备配置与管理（医院设备配置、医院设备招标采购、医疗设备场地建设等）
- □ 项目规划设计（建筑规划设计、医疗工艺流程设计、结构设计等）
- □ 医院工程建设（装饰装修工程、净化工程、建筑智能化、园林景观工程等）
- □ 项目实施管理（项目施工管理、成本和进度控制与管理、招投标管理、工程评奖管理）
- □ 医院运营管理（科室管理、诊疗流程管理、医务管理等）
- □ 其他 (请注明) ________________

3. 您所在机构主要参与医疗建设的哪些阶段?

- □ 规划 / 策划
- □ 设计
- □ 制造 / 生产
- □ 施工 / 建造
- □ 运营

4. 您已经在建筑行业从事多少年工作?

- □ 0-5
- □ 6-10
- □ 11-15
- □ 16-20
- □ >20

5. 您所在机构的名称是什么？ (可选) ____

6. 您所在机构的规模有多大

- □ 微型 (< 10 人)
- □ 小型 (< 50 人)
- □ 中型 (< 250 人)
- □ 大型 (>250 人)

第 2 部分 – 采用建筑工业化和数字技术的现状

7. 您的机构在已执行的医疗项目中采用了哪些建筑工业化的策略:

- □ 构件预制化生产
- □ 现场装配式施工
- □ 建筑设计标准化
- □ 部品生产工厂化
- □ 制造施工机械化
- □ 过程管理信息化
- □ 其他 (请说明) ________________

8. 您的机构当前有多少比例的项目采用了建筑工业化策略:

- □ 无
- □ 0-25%
- □ 25-50%
- □ 50-75%
- □ 75-100%

9. 相比传统施工方式，采用装配式策略是否提高了您所在机构的医疗建设项目的效率:

- □ 未采用装配式技术
- □ 效率降低，反而为了进行装配式需要投入额外的资源
- □ 没有提高，与传统方式区别不大
- □ 少许提高，但面临很大的设计、技术或管理障碍
- □ 极大提高，装配式技术适合您的机构进行的医院建设

10. 您的机构利用了哪些数字化技术来推动医疗建设:

- □ 建筑信息模型（BIM）
- □ 虚拟现实（VR）/ 增强现实（AR）
- □ 物联网（IoT）/ 传感器
- □ 3D 打印
- □ 区块链技术
- □ 机器人（臂）/ 无人机
- □ 数字孪生

- □ 人工智能 / 机器学习
- □ 云计算
- □ 5G 网络
- □ 其他 (请说明) ________________

11. 您的机构当前有多少比例的项目采用了数字化技术:

- □ 无
- □ 0-25%
- □ 25-50%
- □ 50-75%
- □ 75-100%

12. 相比传统施工方式，采用数字技术是否提高了您所在机构的医疗建设项目的效率:

- □ 未采用数字技术
- □ 效率降低，反而为了进行数字化需要投入额外的资源
- □ 没有提高，与传统方式区别不大
- □ 少许提高，但面临很大的设计、技术或管理障碍
- □ 极大提高，数字技术适合您的机构进行的医院建设

第 3 部分 - 采用建筑工业化和数字技术的驱动力和障碍

13. 您认为您所在机构进行装配式医院建设的主要动力是什么:

- □ 增加成本的确定性
- □ 增加工期的确定性
- □ 实现规模经济
- □ 加强平台能力
- □ 减少现场作业时间
- □ 减少现场作业成本
- □ 减少所需劳动力数量
- □ 解决缺乏劳动力的问题
- □ 满足工厂化制造的要求
- □ 进行更高质量的设计
- □ 提升自动化水平
- □ 减少现场作业对环境的影响
- □ 增强全生命周期的环保表现
- □ 减少受限制场地的影响
- □ 政策要求 / 政策奖励
- □ 企业整体战略要求
- □ 顾客要求
- □ 其他 (请说明) ________________

14 您认为您所在机构进行装配式医院建设的主要阻力是什么:

- □ 较难进行设计变更

- □ 较高的设计成本
- □ 难以实现规模经济效益
- □ 风险规避的文化
- □ 客户质疑这种建设方式
- □ 市场需求有限
- □ 缺乏政府激励
- □ 历史失误造成的态度障碍
- □ 相关的设计标准和指导方针很少
- □ 相关技能的劳动力短缺
- □ 分散化的产业结构
- □ 项目团队之间缺乏长期合作
- □ 产能不足
- □ 组织机制不利于进行装配式
- □ 缺乏相应的实践经验
- □ 其他 (请说明) ________________

15. 您认为您所在机构进行 BIM 发展的主要动力是什么:

- □ 增加成本的确定性
- □ 增加工期的确定性
- □ 实现规模经济
- □ 加强平台能力
- □ 减少现场作业时间
- □ 减少现场作业成本
- □ 减少所需劳动力数量
- □ 解决缺乏劳动力的问题
- □ 满足工厂化制造的要求
- □ 进行更高质量的设计
- □ 提升数字化水平
- □ 减少现场作业对环境的影响
- □ 增强全生命周期的环保表现
- □ 减少受限制场地的影响
- □ 政策要求 / 政策奖励
- □ 企业整体战略要求
- □ 顾客要求
- □ 其他 (请说明) ________________

16 您认为您所在机构进行 BIM 发展的主要阻力是什么？:

- □ 较难进行设计变更
- □ 难以实现规模经济效益
- □ 风险规避的企业文化
- □ 客户质疑 BIM 方式
- □ 市场需求有限
- □ 供应链上下游均未使用 BIM
- □ 缺乏面向国内的 BIM 工具
- □ 模型开发工作量增加

- □ 组织机制不利于进行正向
- □ 对协作的消极态度
- □ 缺乏完善的基于 BIM 的工作流程
- □ BIM 实施争议解决机制不成熟
- □ 缺乏各专业间互动
- □ 缺乏对中国 BIM 实施的研究
- □ 培训人员所需的成本和时间
- □ BIM 专家和工具的成本增加
- □ 设计成本增加
- □ 缺乏 BIM 标准
- □ 缺乏 BIM 实施的标准合同形式
- □ 其他 (请说明) ________________

第 4 部分– 采用建筑工业化和数字技术的适当策略

17. 您的机构是否在医疗建设中采取了与其他建筑类不同的装配式设计和建造方法?

- □ 是，医疗建筑的装配式方法与其他建筑类型显著不同
- □ 否，各种类型建筑采取了类似的方法
- □ 不存在上述情况，所在机构只从事医疗建设项目
- □ 所在机构未进行过相关实践

18. 您的机构采取了什么策略来减少医疗项目中实施装配式建造的障碍?

1. ________________
2. ________________
3. ________________
4. ________________
5. ________________

19. 对于整个医疗建设领域，您是否认为有必要提升装配式医院的项目比例?

- □ 是，装配式有利于医疗建设，可以促进设计与施工效率
- □ 否，装配式的形式大于内容，不适应于当前和短期内医疗建设的需求

20. 您的机构是否在医疗建设中采取了与其他建筑类型不同的 BIM 设计和建造方法?

- □ 是，医疗建筑的 BIM 方法与其他建筑类型显著不同
- □ 否，各种类型建筑采取了类似的方法
- □ 不存在上述情况，所在机构只从事医疗建设项目
- □ 所在机构未进行过相关实践

21. 您的机构采取了什么策略来减少医疗项目中实施 BIM 的障碍?

1. ________________
2. ________________
3. ________________
4. ________________
5. ________________

22. 对于整个医疗建设领域，您是否认为有必要提升医院项目里应用 BIM 的比例?

- □ 是，BIM 有利于医疗建设，可以促进设计与施工效率
- □ 否，BIM 的形式大于内容，不适应于当前和短期内医疗建设的需求

23. 您是否愿意参与后续深入访谈研究?

- □ 是, 请注明联系方式 (如微信号)

____

- □ 否, 我不想参与。

感谢您对本研究的支持!

Appendix 2 – Participant information sheet in Chinese

建筑从业人员参与者信息表

伦敦大学学院研究伦理委员会批准编号：18187/001

研究名称：基于建筑信息模型 (BIM)驱动的面向制造和装配式设计：来自医院建设的经验

研究人员的姓名和联系方式：

- **谭 坦**
  伦敦大学学院(UCL)博士研究生，电子邮箱：tan.tan.17@ucl.ac.uk

您受邀参加一个探索中国建筑业转型的研究项目。 在您决定参与之前，了解我们为什么要进行研究以及参与将涉及哪些内容对您来说很重要。 如果您愿意，请花时间仔细阅读以下信息。 如有任何不清楚的地方或者您需要更多的信息，请询问我们。

1. 项目的目的是什么?

该研究项目旨在探索装配式建筑设计和/或 BIM 在医疗建设项目中的应用，旨在通过中国的实际工程项目，做一个多案例比较研究。目前已经搜集武汉火神山医院，北京的一个在建装配式钢结构医院和江西的一个在建装配式混凝土结构的医院。

2. 为什么选择我?

由于您在建筑行业中的角色，您被选中参与这项研究。 我们将与来自不同建筑相关组织的建筑专业人士进行多达 60 次访谈，并在供应链的不同位置对建筑转型所面临的挑战进行比较深入的了解。

3. 我参与之后将会有什么发生?

最多 2 名研究团队成员将参加访谈。 采访将被录音以供日后转录文字。 面试问题将是关于您在实践中使用的 BIM 或装配式设计的策略行动。 每次面试将持续大约一个小时，并且是半结构化的。 也就是说，研究人员将有一个预先准备好的问题清单，这些问题将构成对话的基础。

4. 我将会被录音吗？以及录音会被如何使用?

是的，采访将由科大讯飞录音机录音。 本研究期间进行的采访录音将仅用于匿名转录。 未经您的书面许可，不得将它们用于其他用途，并且不允许项目以外的任何人访问原始录音。 录音将被转录，这些转录将构成研究人员分析的基础。 密码保护和双锁系统将用于安全存储。录音后，一旦可行，文件将在从录音设备中删除。

5. 我的参与会被保密吗?

我们在研究过程中收集的有关您的所有信息都将严格保密。 您将无法在随后的任何报告或出版物中被识别出来。 保密将受到法律约束和专业准则的约束。

Appendix 3 – Consent form for interviews in Chinese

改造建筑网络+

知情同意声明

阅读完信息表和/或听完有关研究的解释后，请填写此表格。

研究标题: 改造建筑网络+: 挑战医院的空间边界-提升现代制造业的能力并推进商业模式

部门: 伦敦大学学院
该研究已由伦敦大学学院研究道德委员会批准：项目ID号：##### 数据保护注册号 Z6364106 / 2019/11/79
姓名和联系方式:

- 研究员: Anne Symons: anne.symons.14@ucl.ac.uk; Phil Astley: p.astley@ucl.ac.uk; Chris Sherwood: Cpsherwood@btinternet.com; Tan Tan (谭坦): tan.tan.17@ucl.ac.uk
- 共同研究员: Dr Chris Goodier: C.I.Goodier@lboro.ac.uk; Dr Jennifer Kingston: j.kingston@cranfield.ac.uk
- 主要研究员: Dr Grant Mills: g.mills@ucl.ac.uk
- 伦敦大学学院 数据保护官: Alexandra Potts data-protection@ucl.ac.uk

感谢您考虑参与这项研究。 在您同意参加之前，组织研究的人员必须向您解释该项目。如果您对信息表或已经给您的解释有任何疑问，请先询问研究人员，然后再决定是否参加。您将随时获得本同意书的副本，以备查阅。**我确认我认同所勾选/签署的下列每个填空，我同意这项研究的内容。 我认同认为未打勾/未签署的方框表示我不同意该部分研究。 我了解，如果不同意任何一项，则我可能被认为不符合这项研究的条件。**

我确认已经阅读并理解了以上研究的信息表。 我有机会考虑这些信息以及对我的期望。 我也有机会提出一些令我满意的问题，并希望参加本研究的访谈。	
我了解在将数据合并到更广泛的数据集中，并且不再可以单独识别之前，我将能够撤回数据。	
我同意参加这项研究。 我了解，除此同意书和联系信息外，无意收集任何个人信息，但收集到的任何其他此类信息将被匿名化。 我了解，根据数据保护法规，’公共任务’将是处理的合法依据。 我也了解我的项目资金与我参与这项研究没有关系。	
将此信息用于此项目 我了解我在这项研究中收集的任何数据都将被匿名安全地存储。 在任何出版物中都无法识别我。	
我了解我的信息可能会受到大学负责人员的审查，以进行监控和审核。	
我了解我的参与是自愿的，并且我可以随时退出而无需给出任何理由。 我了解，如果我决定撤回，除非我另行同意，否则我到目前为止提供的任何可单独识别的个人数据都将被删除。	
我了解参加这项研究的潜在风险。	
我了解信息表中所述的参与可能的直接/间接收益。	
我了解这些数据将不会提供给任何商业组织，而仅由从事这项研究的研究人员负责。	

我了解，我将不会从这项研究或将来可能产生的任何结果中获得经济利益。	
我同意匿名的研究数据可能会被其他人用于未来的研究。	
我了解我提交的信息将作为报告发布，我希望收到它的副本。	
我同意接受采访录音，并理解录音被转录文字后会立即销毁。 如果您不想您的参与被录音，您仍然可以参加研究。	
(a) 我在此确认：我了解信息表中详细列出的排除标准，研究人员向我解释了排除标准； 而且我不属于排除标准。 (b) 在过去12个月中，我已将我目前正在参与或参与的任何其他研究告知研究人员。	
我知道如果我要投诉，应该联系谁。	
我自愿同意参加这项研究。	
在此项目及其他方面使用信息 我对匿名提供的数据将存储在伦敦大学学院研究数据存储服务中感到高兴。 不会有任何个人信息上载到研究数据存储服务。 我了解其他研究人员将可以访问我的匿名数据。	

如果您希望保留联系信息，以便将来希望邀请您参加该项目的后续研究或类似性质的未来研究的伦敦大学学院研究人员与您联系，请在 下面的适当方框。

是的，我很高兴以这种方式与您联系 ☐

不，我不想联系 ☐

________________________ ________________ ________________________

参加者姓名 日期 签名

________________________ ________________ ________________________

研究者 日期 签名

Appendix 4 - Survey result in English

1. Please describe the type of institution you are working for

Options	Percentage %	Subtotal
Owner	15.30%	28
Designer	18.60%	34
Consulting service	9.80%	18
Construction contractor	37.70%	69
Construction equipment supplier	4.90%	9
Medical equipment supplier	3.30%	6
Decoration material supplier	1.60%	3
Operation service provider	4.90%	9
Other____	3.80%	7
Effective filling amount		183

2. Please describe your job type

Options	Percentage %	Subtotal
Pre-planning of hospital projects	5.50%	10
Hospital equipment configuration and management	4.90%	9
Project planning and design	23.50%	43
Hospital engineering construction	24.00%	44
Project implementation management	31.10%	57
Hospital operation management	4.90%	9
Other____	6.00%	11
Effective filling amount		183

3. What stages of healthcare construction your institution is mainly involved in

Options	Percentage %	Subtotal
Planning	30.10%	55
Design	41.50%	76
Manufacture	15.80%	29
Construction	54.60%	100
Operation	19.70%	36
Other____	3.80%	7
Effective filling amount		183

4. How many years have you been in the construction industry

Options	Percentage %	Subtotal
0-5	20.80%	38
6-10.	46.40%	85
11-15.	18.60%	34
16-20	5.50%	10
> 20	8.70%	16

Effective filling amount		183

5. What is the size of your institution		
Options	Percentage %	Subtotal
Miniature (1-10 人)	2.70%	5
Small (11-50 人)	22.40%	41
Medium (51-250 人)	43.70%	80
Large (＞250 人)	31.10%	57
Effective filling amount		183

6. What is the name of your institution (optional)		
No.	Text answers	Submission time
259	罗翔设计有限公司	2021-10-27T10:28:14 +08:00
258	国医科技	2021-10-22T22:38:39 +08:00
256	北京三建	2021-10-21T22:06:54 +08:00
254	湖南省交通规划勘察设计院	2021-10-19T10:32:51 +08:00
251	成都建工	2021-10-15T17:58:08 +08:00
250	云南亚康博医疗	2021-10-15T17:55:18 +08:00
246	乐山昶康心血管病医院	2021-10-15T16:48:35 +08:00
241	江苏正庆建设工程有限公司	2021-10-15T15:14:32 +08:00
237	中安筑邦	2021-10-15T13:59:30 +08:00
236	开平住宅建筑工程集团有限公司	2021-10-15T13:46:14 +08:00
235	海迪设计	2021-10-15T13:27:40 +08:00
233	钢结构集团有限公司	2021-10-15T13:12:40 +08:00
231	中建集团	2021-10-15T13:11:54 +08:00

227	甘肃和诚工程咨询设计有限公司	2021-10-15T12:59:05 +08:00
223	材料员	2021-10-15T12:56:30 +08:00
222	不方便透露	2021-10-15T12:56:04 +08:00
220	中铁四局	2021-10-15T12:53:02 +08:00
218	江苏富盈汇林达建筑科技有限公司	2021-10-15T11:36:06 +08:00
216	中海建筑有限公司	2021-10-15T10:49:23 +08:00
214	建筑设计	2021-10-15T10:25:44 +08:00
Note: For more details, please export the original data		

7. What construction industrialization strategies your institution has adopted in its healthcare projects

Strategies	0 (none)	1	2	3	4
Most of the building components are manufactured in the factory	7	15	42	82	37
The construction site adopts the method of prefabricated assembly	4	20	53	72	34
A standardised component system has been established	7	22	30	74	50
Construction is carried out using machinery or robots	25	30	59	52	17
Information management system for the whole production process	9	21	44	82	27
Assembled building structure systems have been designed	9	19	51	78	26
Adopt a standardised approach to building design	5	8	49	68	53
Effective filling amount	183				

8. What design strategies your institution has adopted to improve manufacturing and assembly capabilities in healthcare projects

	0 (none)	1	2	3	4 (very much)
Error-check in the design	2	17	45	75	44
Design with options that make it easier to manufacture building components	3	15	50	76	39

Design with simpler and easier-to-operate building components in mind	4	14	42	75	48
Designed with pre-determined building component assembly techniques in mind	3	7	47	88	38
Design multi-functional and multi-purpose parts/building components	6	19	51	77	30
Consider modular design	6	14	55	69	39
Consider designs for mechanized or automated assemblies	8	17	46	76	36
Use standardised or off-the-shelf components	4	13	41	84	41
Use similar materials	7	15	56	66	39
Use eco-friendly materials	4	11	37	73	58
Reduce the number of parts	5	18	53	64	43
Minimize the number of connectors	5	20	50	75	33
Standardising the type of connectors	4	12	46	79	42
Minimize the use of fragile parts/building components	4	18	47	70	44
Increase fault tolerance and do not overspecify the margin of error	2	12	43	83	43
Effective filling amount	183				

9. What percentage of your institution's current hospital projects employ construction industrialization strategies		
Options	Percentage %	Subtotal
0-20%	13.70%	25
20-40%	37.70%	69
40-60%	32.80%	60
60-80%	13.70%	25
80-100%	2.20%	4
Effective filling amount		183

10. Compared with the traditional construction method of hospital construction, the adoption of the construction industrialization strategy has brought about a large degree of change at the project level					
	-2 (strongly disagreed)	-1	0	1	2 (Strongly agree)
Reduced labor costs	4	6	16	102	55
Enhanced production safety	6	2	23	80	72
Improved product quality	2	5	27	77	72

Reduced construction duration	4	7	28	70	74
Reduced waste of resources	3	8	24	85	63
Reduced construction cost	11	20	43	72	37
Effective filling amount	183				

11. What digital technologies your institution uses in its healthcare projects					
	0 (none)	1	2	3	4 (very much)
BIM	7	5	32	79	60
VR / AR	26	30	64	49	14
IoT/Sensor	16	16	60	72	19
3D Printing / Additive Manufacturing	37	39	46	46	15
Blockchain technology	34	35	49	56	9
Robot (arm) / drone	34	34	57	43	15
Digital twin	41	37	47	47	11
Artificial Intelligence / Machine Learning	37	32	52	43	19
Cloud computing	27	23	39	60	34
5G network	14	24	38	59	48
Effective filling amount	183				

12. What percentage of your instituts's current hospital projects are digitally enabled		
Options	Percentage %	Subtotal
0-20%	23.00%	42
20-40%	36.60%	67
40-60%	26.80%	49
60-80%	12.60%	23
80-100%	1.10%	2
Effective filling amount		183

13. Compared with the traditional construction method of hospital construction, the use of digital technology has brought about a large degree of change at the project level					
	-2 (strongly disagreed)	-1	0	1	2 (Stron

					gly agree)
Reduced labor costs	2	5	21	92	63
Enhanced production safety	2	2	30	78	71
Improved product quality	5	2	27	81	68
Reduced construction duration	4	4	26	78	71
Reduced waste of resources	4	7	22	90	60
Reduced construction cost	10	13	40	77	43
Effective filling amount	183				

14. In hospital construction, the main factors that influence whether your institution adopts construction industrialization					
	-2 (strongly disagreed)	-1	0	1	2 (Strongly agree)
Can improve product quality	3	4	17	89	70
Can improve the competitiveness of the company	2	3	19	72	87
Good compatibility with current business	3	6	37	81	56
The technical difficulty is not complicated	6	23	42	65	47
The mechanism for the various professions to work together is not complicated	5	22	34	80	42
The company's top manager supports the construction industrialization	4	9	28	80	62
The company has the hardware and software resources and team required for the construction industrialization	7	15	26	79	56
The company has the ability to adapt to new technologies quickly	6	9	27	76	65
Pressure from competitors to use the construction industrialization path	4	9	29	89	52
The customer wants to use the construction industrialization	4	6	42	84	47
It is a policy and industry trend requirement	1	6	18	82	76
Requires less ongoing investment and hardware and software support	6	16	38	71	52
This increases the benefits	6	13	38	74	52
This increases the business	4	8	32	84	55

The construction industrialization strategy is simple to implement	6	19	27	79	52
Productivity can be increased	3	6	15	78	81
Customer satisfaction can be improved	2	13	31	79	58
The company is willing to adopt and support the construction industrialization	3	9	18	94	59
Effective filling amount	183				

15. In hospital construction, the main factors affecting whether your institution adopts BIM or not					
	-2 (strongly disagreed)	-1	0	1	2 (Strongly agree)
Can improve product quality	2	3	20	90	68
Can improve the competitiveness of the company	2	5	28	81	67
Good compatibility with current business	4	8	40	68	63
The technical difficulty is not complicated	4	20	43	62	54
The mechanism for the various professions to work together is not complicated	2	18	40	74	49
The company's top manager supports BIM	6	10	31	65	71
The company has the hardware and software resources and team required for BIM	6	9	34	65	69
The company has the ability to adapt to new technologies quickly	4	14	23	88	54
Pressure from competitors to use BIM	5	6	42	75	55
The customer wants to use BIM	7	6	42	79	49
It is a policy and industry trend requirement	3	7	26	85	62
Requires less ongoing investment and hardware and software support	9	18	38	86	32
This increases the benefits	4	15	42	67	55
This increases the business	3	3	38	89	50
BIM implementation is simple	4	16	39	80	44
Productivity can be increased	3	5	25	81	69
Customer satisfaction can be improved	1	2	28	80	72

The company is willing to adopt and support BIM	3	10	23	89	58
Effective filling amount	183				

16. Your institution has adopted a different construction industrialization strategy from other building types (e.g. residential, office) in healthcare construction		
Options	Percentage %	Subtotal
-2	1.60%	3
-1	4.90%	9
0	15.30%	28
1	59.60%	109
2	18.60%	34
3	0.00%	0
4	0.00%	0
5	0.00%	0
Effective filling amount		183

17. What strategies has your institution adopted to reduce barriers to the construction industrialization in healthcare projects?		
No	Text answers	Submission time
259	not	2021-10-27T10:28:14 +08:00
258	Increase investment	2021-10-22T22:38:39 +08:00
256	The two sides negotiated to solve the problems in the project	2021-10-21T22:06:54 +08:00
253	not	2021-10-15T23:32:56 +08:00
250	New technology	2021-10-15T17:55:18 +08:00
246	Steel structural components	2021-10-15T16:48:35 +08:00
241	BIM	2021-10-15T15:14:32 +08:00
237	not	2021-10-15T13:59:30 +08:00
236	Select management team members when hiring	2021-10-15T13:46:14 +08:00
235	BIM	2021-10-15T13:27:40 +08:00

	233	Inconvenient to disclose	2021-10-15T13:12:40+08:00
	229	economize	2021-10-15T13:01:59+08:00
	227	BIM	2021-10-15T12:59:05+08:00
	226	bim	2021-10-15T12:58:49+08:00
	225	Intelligent system	2021-10-15T12:58:23+08:00
	224	Promote standardised design	2021-10-15T12:57:55+08:00
	222	Mechanized, refined	2021-10-15T12:56:04+08:00
	219	not	2021-10-15T12:52:51+08:00
	218	Standardise operations	2021-10-15T11:36:06+08:00
	216	Government cooperation	2021-10-15T10:49:23+08:00
Note: For more details, please export the original data			

18. For the entire industry of healthcare construction, you believe that it is necessary to increase the proportion of construction industrialization

Options	Percentage %	Subtotal
-2	1.10%	2
-1	1.60%	3
0	10.90%	20
1	44.80%	82
2	41.50%	76
3	0.00%	0
4	0.00%	0
5	0.00%	0
Effective filling amount		183

19. Your institution has adopted a different BIM design and construction approach than other building types (e.g. residential, office) in healthcare construction

Options	Percentage %	Subtotal
-2	2.20%	4
-1	1.10%	2
0	17.50%	32
1	55.70%	102

2	23.50%	43
3	0.00%	0
4	0.00%	0
5	0.00%	0
Effective filling amount		183

20. What strategies has your institution adopted to reduce barriers to implementing BIM in healthcare projects?

No	Text answers	Submission time
259	not	2021-10-27T10:28:14 +08:00
258	Introduction of advanced technology	2021-10-22T22:38:39 +08:00
256	The three parties complete it together and restrict each other	2021-10-21T22:06:54 +08:00
253	not	2021-10-15T23:32:56 +08:00
250	Integration	2021-10-15T17:55:18 +08:00
247	Increase budget	2021-10-15T16:56:34 +08:00
246	not	2021-10-15T16:48:35 +08:00
241	Increase capital investment and talent training	2021-10-15T15:14:32 +08:00
237	not	2021-10-15T13:59:30 +08:00
229	There are no obstacles	2021-10-15T13:01:59 +08:00
227	Organise learning	2021-10-15T12:59:05 +08:00
226	optimise	2021-10-15T12:58:49 +08:00
224	Strengthen BIM software training	2021-10-15T12:57:55 +08:00
222	Manage effectively	2021-10-15T12:56:04 +08:00
219	not	2021-10-15T12:52:51 +08:00

218	Lightweight standardisation, real-time monitoring	2021-10-15T11:36:06 +08:00
216	Fault tolerance for mechanical and electrical fire decoration reduces costs	2021-10-15T10:49:23 +08:00
215	Accumulate, refine, organise, and summarize BIM family libraries	2021-10-15T10:38:26 +08:00
214	Use environmentally friendly materials	2021-10-15T10:25:44 +08:00
212	A common approach to consensus within the same industry	2021-10-15T10:24:36 +08:00
Note: For more details, please export the original data		

21. For the entire industry of healthcare construction, you believe that it is necessary to increase the proportion of BIM used		
Options	Percentage %	Subtotal
-2	1.60%	3
-1	0.50%	1
0	10.90%	20
1	44.30%	81
2	42.60%	78
3	0.00%	0
4	0.00%	0
5	0.00%	0
Effective filling amount		183

22. Would you like to participate in a follow-up interview study?		
Options	Percentage %	Subtotal
No, I don't want to participate	64.00%	114
Yes, my WeChat or mobile phone contact details are ____	36.00%	64
Effective filling amount		178

Appendix 5 - Participant information sheet in English

Participant Information Sheet For Construction Practitioners
UCL Research Ethics Committee Approval ID Number: _______

YOU WILL BE GIVEN A COPY OF THIS INFORMATION SHEET

Title of Study: BIM-enabled Design for Manufacture and Assembly in Healthcare Construction

Department: The Bartlett School of Construction and Project Management

Name and Contact Details of the Researcher(s):

- **Tan Tan**
  Bartlett School of Construction and Project Management, University College London, 1-19 Torrington Place, London WC1E 7HB. Email: tan.tan.17@ucl.ac.uk
- **Dr Eleni Papadonikolaki**
  Bartlett School of Construction and Project Management, University College London, 1-19 Torrington Place, London WC1E 7HB. Email: e.papadonikolaki@ucl.ac.uk

Name and Contact Details of the Principal Researcher:

- **Dr Grant Mills**
  Bartlett School of Construction and Project Management, University College London, 1-19 Torrington Place, London WC1E 7HB. Email: g.mills@ucl.ac.uk

You are being invited to take part in a research project exploring the transformation of the UK construction industry. Before you decide to participate it is important for you to understand why the research us being done and what participation will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part. Thank you for reading this.

6. **What is the project's purpose?**
   This research project has been established to explore BIM-enabled Design for Manufacture and Assembly (DfMA) in healthcare construction.

7. **Why have I been chosen?**
   You have been chosen to participate in this research because of your role in the construction industry. We will be conducting up to 60 interviews with construction professionals from various construction related organisations, and at different places in the supply chain to develop comparative insights into the challenges of transforming construction.

8. **Do I have to take part?**
   It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form.

   You can withdraw your consent for our use of your responses until the data from your participation has been incorporated into a broader dataset and is no longer separately identifiable. You can withdraw without giving a reason and without it affecting any benefits that you are entitled to. If you decide to withdraw you will be asked what you wish to happen to the data you have provided up that point.

9. **What will happen to me if I take part?**
   The interviews will be attended by up to 2 members of the research team. The interviews will be recorded for later transcription. Each interview will last approximately an hour, and be semi-structured. That is, the researchers will have a pre-prepared list of questions that will form the basis of a conversation exploring your views on transforming construction, and your organisation's response to the agenda.

10. **Will I be recorded and how will the recorded media be used?**
    Yes, the interviews will be audio recorded. The audio recordings of the interview made during this research will be used only for transcription. No other use will be made of them without your written permission, and no one outside the project will be allowed access to the original recordings. The recordings will be transcribed and these transcriptions will form the basis of the researchers' analysis.

    As soon as practical after the recording, the files will be removed from the recording device to a UCL hosted, closed and password protected MS SharePoint site for the duration of the research along with transcriptions. Research data files will be password protected to restrict access to the UCL research teams. Audio files will be deleted from the MS SharePoint site after the transcriptions have been validated.

11. **What are the possible disadvantages and risks of taking part?**
    We have not identified any disadvantages or risks of taking part in this research. However, if you have any concerns, please discuss them with the research team. If you are unhappy with the response from the researchers, please contact Mr Tan at the address above.

12. **What are the possible benefits of taking part?**
    Whilst there are no immediate benefits for those people participating in the project, this work is intended to inform industrial strategies and academic debate and enhance the long-term productivity of the construction industry.

13. **What if something goes wrong?**
    If you have a complaint about the research or research conduct, please contact Mr Tan, Bartlett School of Construction and Project Management, University College London, 1-19 Torrington Place, London WC1E 7HB email: tan.tan.17@ucl.ac.uk

    Should you feel your complaint has not been handled to your satisfaction, you can contact the Chair of the UCL Research Ethics Committee – ethics@ucl.ac.uk

14. **Will my taking part in this project be kept confidential?**
    All the information that we collect about you during the course of the research will be kept strictly confidential. You will not be able to be identified in any ensuing reports or publications.

15. **Limits to confidentiality**
    Confidentiality will be respected subject to legal constraints and professional guidelines. If there are compelling and legitimate reasons for this to be breached, we would inform you of any decisions that might limit your confidentiality.

16. **What will happen to the results of the research project?**
    The data from our study will form the basis of academic research papers and Ph.D. research of The Bartlett School of Construction and Project Management, UCL.

17. **Local Data Protection Privacy Notice**

Notice:
The controller for this project will be University College London (UCL). The UCL Data Protection Officer provides oversight of UCL activities involving the processing of personal data, and can be contacted at data-protection@ucl.ac.uk

This 'local' privacy notice sets out the information that applies to this particular study. Further information on how UCL uses participant information can be found in our 'general' privacy notice:

For participants in research studies, click here

The information that is required to be provided to participants under data protection legislation (GDPR and DPA 2018) is provided across both the 'local' and 'general' privacy notices.

The categories of personal data used will be as follows:

The lawful basis that will be used to process your personal data is: 'Public task' for

personal data.

Your personal data will be processed so long as it is required for the research project. If we are able to anonymise or pseudonymise the personal data you provide we will undertake this, and will endeavour to minimise the processing of personal data wherever possible.

If you are concerned about how your personal data is being processed, or if you would like to contact us about your rights, please contact UCL in the first instance at data-protection@ucl.ac.uk.

15. Contact for further information
You should give the participant a contact point for further information. This can be your name, address and telephone number or that of another researcher in the project (if this is a supervised-student project, the address and telephone number of the student's supervisor).

Finally the information sheet should state that the participant will be given a copy of the information sheet and, if appropriate, a signed consent form to keep and remember to thank the participants taking part in the project.

Thank you for reading this information sheet and for considering to take part in this research study.

Appendix 6 - Consent form for interviews in English

CONSENT FORM FOR *CONSTRUCTION PRACTITIONERS* IN RESEARCH STUDIES
Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.
Title of Study: BIM-enabled Design for Manufacture and Assembly in Healthcare Construction
Department: Bartlett School of Construction and Project Management, UCL
Name and Contact Details of the Researcher(s): Tan Tan tan.tan.17@ucl.ac.uk; Eleni Papadonikolaki e.papadonikolaki@ucl.ac.uk
Name and Contact Details of the Principal Researcher: Dr Grant Mills g.mills@ucl.ac.uk
Name and Contact Details of the UCL Data Protection Officer: Alexandra Potts data-protection@ucl.ac.uk
This research has been approved by the UCL Research Ethics Committee: Project ID number: ___________

Thank you for considering taking part in this research. The person organising the research must explain the project to you before you agree to take part. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

I confirm that I understand that by ticking/initialling each box below I am consenting to this element of the study. I understand that it will be assumed that unticked/initialled boxes means that I DO NOT consent to that part of the study. I understand that by not giving consent for any one element that I may be deemed ineligible for the study.

		Tick Box
	*I confirm that I have read and understood the Information Sheet for the above study. I have had an opportunity to consider the information and what will be expected of me. I have also had the opportunity to ask questions which have been answered to my satisfaction, and would like to take part in the interviews for this research.	
	* I understand that I will be able to withdraw my data until that data has been incorporated into a broader dataset and is no longer separately identifiable.	
	* I consent to participate in the study. I understand that there is no intention to collect any personal information beyond this consent form and contact information, but that any other such information collected will be anonymised. I understand that according to data protection legislation, ‘public task’ will be the lawful basis for processing. I also understand that my project funding is not linked to my participation in this research.	
	Use of the information for this project only * I understand that my data gathered in this research will be stored anonymously and securely. It will not be possible to identify me in any publications.	
	* I understand that my information may be subject to review by responsible individuals from the University for monitoring and audit purposes.	
	* I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason. I understand that if I decide to withdraw, any personal data I have provided up to that point that is separately identifiable, will be deleted unless I agree otherwise.	
	I understand the potential risks of participating and the support that will be available to me should I become distressed during the course of the research.	
	I understand the direct/indirect benefits of participating.	
	I understand that the data will not be made available to any commercial organisations but is solely the responsibility of the researcher(s) undertaking this research.	

	I understand that I will not benefit financially from this research or from any possible outcome it may result in in the future.	
	I understand that I will be compensated for the portion of time spent in the study (if applicable) or fully compensated if I choose to withdraw.	
	I agree that my anonymised research data may be used by others for future research. [No one will be able to identify you when this data is shared.]	
	I understand that the information I have submitted will be published as a report and I wish to receive a copy of it. Yes/No	
	I consent to my interview being audio recorded and understand that the recordings will be destroyed immediately following transcription. If you do not want your participation recorded you can still take part in the study.	
	I hereby confirm that I understand the inclusion criteria as detailed in the Information Sheet and explained to me by the researcher.	
	I hereby confirm that: (a) I understand the exclusion criteria as detailed in the Information Sheet and explained to me by the researcher; and (b) I do not fall under the exclusion criteria.	
	I agree that my GP may be contacted if any unexpected results are found in relation to my health.	
	I have informed the researcher of any other research in which I am currently involved or have been involved in during the past 12 months.	
	I am aware of who I should contact if I wish to lodge a complaint.	
	I voluntarily agree to take part in this research.	
	Use of information for this project and beyond I would be happy for the data I provide, once anonymised, to be archived in the UCL Research Data Storage Service. No personal information will be uploaded to the Research Data Storage Service. I understand that other researchers will have access to my anonymised data.	

If you would like your contact details to be retained so that you can be contacted in the future by UCL researchers who would like to invite you to participate in follow up studies to this project, or in future studies of a similar nature, please tick the appropriate box below.

	Yes, I would be happy to be contacted in this way	
	No, I would not like to be contacted	

____________________________ ________________ ____________________

Name of participant Date Signature

________________________ ________________ ____________________

Researcher Date Signature

Appendix 7 - Research Paper Declaration

Parts of this research have been published via eight research papers for the dissemination, including four journal papers, one book chapter and three conference paper, used in this research. Four of them are used for chapters related to the literature review of modularity theory and DfMA. One of them is used for chapter 3, 4, 6 and 7.

1. **Tan, T***., Mills, G., Papadonikolaki, E., Li, B., & Huang, J. (2022). Digital-enabled Design for Manufacture and Assembly (DfMA) in Offsite Construction: A Modularity Perspective for the Product and Process Integration. *Architectural, Engineering and Design Management*. 1-16.
2. **Tan, T***., Mills, G., & Papadonikolaki, E. (2022). Building information modeling-enabled platform approach to design for manufacture and assembly. In *Research Companion to Building Information Modeling* (pp. 373-394). Edward Elgar Publishing.
3. **Tan, T***., Mills, G., Hu, J., & Papadonikolaki, E. (2021). Integrated Approaches to Design for Manufacture and Assembly: A Case Study of Huoshenshan Hospital to Combat COVID-19 in Wuhan, China. *Journal of Management in Engineering, 37*(6), 05021007.
4. Lu, W., **Tan, T***., Xu, J., Wang, J., Chen, K., Gao, S., & Xue, F. (2021). Design for Manufacture and Assembly in construction: The old and the new. *Architectural, Engineering and Design Management, 17*(1-2), 77-91.
5. **Tan, T.**, Lu, W*., Tan, G., Xue, F., Chen, K., Xu, J., Wang, J., & Gao, S. (2020). Construction-oriented design for manufacture and assembly (DfMA) guidelines. *Journal of Construction Engineering and Management, 148*(8), 04020085.
6. **Tan, T***., Mills, G., Papadonikolaki, E., Xu, Y., & Chen, K. (2022). Building Information Modelling in Healthcare Design and Construction: a Bibliometric Review and Systematic Review. In *International Conference on Computing in Civil and Building Engineering (ICCCBE 2022)*.

7. **Tan, T***., Papadonikolaki, E., Mills, G., Chen, J., Zhang, Z., & Chen, K. (2021). BIM-enabled Sustainability Assessment of Design for Manufacture and Assembly. In *38th International Symposium on Automation and Robotics in Construction (ISARC 2021)*.

8. **Tan, T***., Mills, G., Papadonikolaki, E., Lu, W., & Chen, K. (2020). BIM-based Design for Manufacture and Assembly. In *27th EG-ICE International Workshop on Intelligent Computing in Engineering (EG-ICE 2020)*.